Fibre and ply orientation measurement in carbon fibre composites from ultrasonic data

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Abstract

There is a growing trend towards using non-destructively derived component geometries to construct FE models, from which as-manufactured component properties can be predicted. In the case of carbon-fibre reinforced polymer (CFRP) components the desired properties are the ply locations, and the ply and fibre orientations. This paper presents methods that can be applied to ultrasonic pulse-echo inspections to obtain these properties. Results from a laminate show that these methods are, in most locations, capable of providing the three-dimensional datasets required for FE model generation.

1. Introduction

The complex geometrical nature of fibre-waviness and ply-wrinkling defects in carbon fibre reinforced polymer composite (CFRP) components makes defining acceptance criteria for manufactured parts a difficult task. The favoured solution is to use finite-element (FE) models of as-manufactured parts to predict the mechanical performance characteristics (1-4). This approach relies on non-destructive methods (typically X-ray CT or pulse-echo ultrasound) being able to image the internal structure to produce a 3D dataset, from which the geometrical properties of the component, including any deviations from design, are extracted. These are subsequently used to construct an FE model, the predictions of which can assist in the quality assurance process.

Information required from a non-destructive inspection to achieve this process includes the component surface locations, ply boundary locations, ply orientations and fibre orientations. The success of this FE-assisted approach relies on robust data-acquisition and inversion techniques that can be applied to non-destructive inspection data to provide location and orientation information.

One solution uses pulse-echo ultrasonic inspections to obtain datasets from which fibre and ply information can be extracted (5,6). Recent advances in the understanding of the interaction of ultrasound with the ply layers and fibre tows (5,7,8) has enabled acquisition of three-dimensional (3D) datasets that have sensitivity to these features. This paper shows how image-processing techniques, specifically structure-tensor (9) and Radon-transform methods (3,10), can be applied to ultrasound data to map ply locations and orientations in CFRP components.

2. Methodology

A pulse-echo full-waveform 2-D raster scan provides the 3D dataset from which orientation and location information is to be extracted. The ‘raw’ waveform data is processed using the Hilbert transform to obtain the instantaneous amplitude and instantaneous phase (5).
Extraction of ply location information utilises phase data, which is ‘locked’ to the ply structure (5). The phase value at different interface types (front surface, back surface, resin layers) is related to the phase at peak amplitude, \( \phi_0 \), in the input pulse. At the composite front surface the phase is \( \phi_0 \), at the back surface is \( \phi_0 - \pi \), and at inter-ply resin layers is \( \phi_0 - \pi/2 \). This phase-based approach is used to produce surface-location and ply-location maps.

Ply orientation is obtained using the structure-tensor method applied to the instantaneous-phase data (9). In this method, gradients in the phase data are used to calculate the normal vector to the ply.

Fibre orientation is measured using a Radon-transform method (3, 10) applied to the instantaneous-amplitude data. In this method the Radon transform of local 2D regions aligned to the local ply structure is calculated. These 2D transforms are reduced to a 1D angular distribution by taking the sum of the absolute gradients at each angle in the Radon transform image. The peak of this angular distribution is taken as the local fibre angle.

3. Data collection and pre-processing

Specific ultrasonic inspection parameters are required to achieve a dataset that has the required sensitivity to fibre and ply features (5,6). A frequency close to the resonance frequency of the plies, and a focal-spot size that can resolve fibre-tow features are a necessity. In this study a 20 MHz, 38 mm (1.5 Inch) focused probe with a 5 mm diameter polymer active element was used. The broad-band nature of the polymer element enables the received waveforms to be filtered to different frequency bands for fibre and ply analysis. A pulse-echo raster scan was acquired from a 23-ply, 3 mm thick quasi-isotropic unidirectional carbon-fibre laminate using an immersion scanning tank. The amplitude and phase data derived from the raw RF waveforms are shown in Figure 1.

![Figure 1](image1.jpg)  
**Figure 1.** Cross sections through (a) instantaneous-amplitude and (b) instantaneous-phase data volumes from which fibre and ply information is extracted using image-processing techniques.
4. Results

Processing the amplitude dataset from Figure 1 using the Radon-transform method results in an in-plane fibre-angle map, as shown in Figure 2(a). The bands of uniform colour indicate the stacking sequence of the plies. The superimposed black lines are derived from the phase dataset, where the $\phi_0 - \pi/2$ phase value, associated with the resin layers at ply boundaries, is mapped to black. This visually indicates the location of the plies and allows double plies to be identified, for example the two 45° (green) double plies. Subtler angular variations become visible upon applying an appropriate colour scale, allowing any deviation from the expected in-plane fibre angle to be visualised.

![Figure 2](image)

(a)

(b)

Figure 2. Cross sections through (a) the in-plane fibre orientation revealing the stacking sequence of the plies and (b) the out-of-plane ply orientation results showing ply angle relative to an x-z slice-plane.

These results can be used to construct FE models where ply locations are true to the specific component. To retrieve the 3D fibre-axis associated with each ply the in-plane fibre orientation is combined with the out-of-plane ply angle measured using the structure-tensor method and shown in Figure 2(b). A greyscale overlay of the phase data from which it has been derived is shown to provide context to the measurements.

5. Conclusions

In this paper a pulse-echo ultrasonic technique has been applied to a CFRP laminate. Results from a structure-tensor method have shown the ability to map out-of-plane ply orientations from the instantaneous-phase data, whilst the in-plane fibre orientations can be determined from the instantaneous-amplitude data using a Radon-transform method. It is expected that this type of analysis can provide the input to FE models so that the performance characteristics of as-manufactured composite parts featuring ply wrinkling and fibre waviness can be evaluated non-destructively.
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References


