Full 3D characterisation of composite laminates using ultrasonic analytic signals

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Abstract

Driven by environmental targets on CO$_2$ emissions, the aerospace and automotive industries are designing lighter structures with composites and are requiring much higher fidelity non-destructive information about the internal structure of manufactured composite components. Consistent research progress over the last decade has gradually revealed a wealth of detailed information within the ultrasonic pulse-echo response from composite laminates. Unlocking that information requires careful treatment of various unwanted effects such as phononic band gaps and phase singularities in the data, followed by inversion methods to convert the ultrasonic data into three-dimensional maps of actual material properties, such as ply-location maps, out-of-plane ply-angle maps and in-plane fibre-orientation maps. From these, any tape gaps and overlaps can be tracked and deviations from the design such as wrinkles can be quantified. This paper presents each stage in the state-of-the-art processes developed by the authors and applies them to real composite specimens.

1. Introduction

In the drive to predict the performance of composite laminates using numerical modelling, there has long been a need to completely characterise the internal structure of the plies and fibre tows within them using a non-destructive inspection method (1-4). Many decades of ultrasound usage to map defects in two dimensions had failed to realise the full potential of the information stored in the pulse-echo waveform response because it is very difficult to unravel such a complex sum of so many different contributions. Recently that information has been unlocked by converting the ultrasonic waveform into an analytic signal and decomposing it into separate instantaneous phase, amplitude and frequency responses, providing the classifiers for the various discontinuities that exist in the structure (5,6). This paper traces the path through the subsequent inversion algorithms to obtain as full a map as possible of the internal microstructure of the material including measurement of any wrinkles using the metrics that have been shown to be the most influential on the compression strength (4). A demonstration is presented for a real aerospace sample containing out-of-plane ply wrinkles and in-plane fibre waviness. It also describes the unwanted effects of phononic band gaps (7) and a way to minimise them.

2. Inversion methodology

The microstructural characterisation of composites is performed in three stages of inversion of the ultrasonic full-waveform data: ply tracking, feature classification and 3D fibre-tow orientation mapping. Initially, a correct zero level has to be set for the...
waveforms and any depth-amplitude correction (DAC) applied, prior to using the Hilbert transform to create the analytic signal, as illustrated in Figure 1.

Figure 1. Analytical model (6) of a wrinkled 8-ply composite in immersion showing 3D ply-tracking gates on the simulated analytic signal for: front surface (red), back surface (blue) and resin layers (green).

2.1 Ply Tracking

The principle on which ply tracking is based is that, when the fundamental ply-resonance frequency is excited in the material, the pulse-echo instantaneous-phase will be locked to the ply structure. For an input pulse with a phase of $\phi_0$ at its peak amplitude, the phase at the front surface, back surface and resin inter-ply layers will be $\phi_0$, $\phi_0 - \pi$ radians and $\phi_0 - \pi/2$ radians respectively (1,6) and these can be detected using 3D gates on the analytic signal - Figure 1.

A one-dimensional normal-incidence analytical model of ultrasonic propagation in composite, described in (6), is used to illustrate ply tracking in Figure 2.

2.2 Feature Classification

Features that can occur in composites are either designed in, such as ply drops, or caused by a non-optimal manufacturing process, such as wrinkles, tape gaps and overlaps. The behaviour of the analytic signal at each of these features is explained in (1) along with feature-classifiers. For example, a feature of a resin layer is that it reflects ultrasound and should cause a peak in the instantaneous amplitude, which also has a negative curvature (second derivative). A wrinkle such as in Figure 2 results in some very thick plies with much lower resonance frequencies. In these, the second-harmonic resonance can be excited preferentially over the fundamental, causing an artefact – erroneous mid-ply resin layers (Figure 2(b)) – that have been removed in Figure 2(c) by rejecting resin-layer indications which are not at a negative curvature of the instantaneous amplitude.
Figure 2. Analytical model (6) of a wrinkled 8-ply composite in immersion showing: (a) diagram of the model with aspect ratio of 50, (b) modelled instantaneous amplitude (greyscale) with overlaid locations of the gate crossings in the same colours as gates in Figure 1: red for front surface, blue for back surface and green for resin layers, and (c) as (b) but with the curvature discriminator - green overlay points have been removed that are not at the peak negative second derivative (curvature).

Another important classifier is the instantaneous frequency, which always drops in a thick ply and in the first and last plies, helping to distinguish the back-wall echo. The instantaneous frequency goes negative and the amplitude goes to zero at a phase singularity, which can be caused by a resin layer becoming as thick as a ply (eg. some of the black spots in Figure 2(c)), such as at a ply drop and either side of a tape gap or tape overlap (1). Another cause of a phase singularity is a phononic band gap at the resonance frequency (7), which develops with depth in the material due to the peak in the reflection coefficient at the resonance frequency. This is only noticed as the resin-layer thickness becomes more than approximately 10% of the ply spacing, which it can do for particle-toughened resin layers used in some aerospace composites. Unfortunately, this artefact causes errors in the ply tracking for plies deeper than the phase singularity, limiting the depth of this method, so it is important to detect it and correct for it as described in section 3.3 below.

2.3 3D fibre-tow orientation mapping

The final stage is to map the 3D orientation of the fibre tows throughout the structure. This is achieved for out-of-plane ply-orientation angles using the instantaneous phase (see sections 2.1 and 2.2) and structure-tensor analysis (8). For in-plane fibre angles, the fibre tows cause variations in the reflection coefficient of the resin layers and, therefore, in the instantaneous amplitude at the corresponding time of flight. These variations can be imaged and processed using a Radon transform method to determine the local in-plane fibre direction (9).
3. Results

An example of the inversion process applied to a real specimen from an aircraft component is shown in this section. The material is made from uni-directional (UD) plies of 0.125 mm thickness and the specimen contains both out-of-plane ply wrinkling and in-plane fibre waviness, so it is particularly difficult to characterise because the plies are not at a constant depth so any horizontal slice through the data cannot be guaranteed to be imaging just one ply across the whole specimen. The ultrasonic pulse-echo response from a polymer probe of centre frequency 18 MHz and -6 dB bandwidth 13 MHz was digitised at a sample rate of 500 MHz over a raster scan of 0.2 mm pitch.

3.1 Pre-processing.

First, a correct zero level was set such that the waveforms have an integral of zero. A DAC had already been applied at acquisition time, prior to digitisation. The data was then low-pass filtered with a cut-off frequency of 15 MHz to avoid second harmonics of the ply resonance; the expected fundamental ply-resonance frequency was approximately 12 MHz.

3.2 Input-pulse instantaneous phase and centre frequency.

The first stage in the inversion process is to determine $\phi_0$, the instantaneous phase at the peak amplitude of the input pulse, and the pulse centre frequency. It has been shown that, for composites within the normal range of front-surface resin-layer thickness, the input-pulse phase and frequency can be determined from an analysis of the front-surface signal (1). In the example shown in the top-left of Figure 3, the analytic signal at the front surface has been analysed for a large part of the scan and plotted in the complex plane, followed by an automatic determination that the instantaneous phase at the peak (green dot and straight line) is 1.91 radians. The centre frequency of the input pulse can be calculated as the ratio of phase difference and time difference between two points – one on the rising edge of the amplitude peak and one on the descending edge after the front-surface peak (red dots and curve). In this case, the centre frequency determined in the front-surface time window (after low-pass filtering at 15 MHz) is 13.4 MHz.

3.3 Removal of phononic band-gap effects

The next issue to deal with is the potential for the development of a phononic band gap in the signal transmitted to deeper layers (7) and the formation of a phase singularity, as described in section 2.2. This can be dealt with by closing the band gap using a customised process where the response is split into low-pass filtered and high-pass filtered waveforms, which are then speeded up and slowed down respectively. The cut-off frequency for both filters is the fundamental resonance frequency and the amount of adjustment to the phase velocity is dependent on the width of the band gap, as explained in (7), which increases with the number of plies passed through. The detail of this method is beyond the scope of this paper but it is currently being trialled and documented fully for a future journal publication.
3.4 Ply tracking.

The next stage of the inversion process is to use the instantaneous amplitude, phase and frequency to detect interface echoes and classify them into front-surface, back-surface and resin-layer reflections. The resultant interface locations are shown superimposed on a 3D map of instantaneous-amplitude in Figure 3. The out-of-plane wrinkling is clearly imaged through the undulations in the resin layers.

Figure 3. The first two stages of the inversion process – input-pulse phase analysis and ply tracking - applied to ultrasonic pulse-echo full-waveform data from an aerospace sample with 0.125 mm plies. Top-left is the analytic-signal plot from the front-surface with a green dot and straight line showing the phase at peak amplitude whilst the red dots and curve are showing the window over the front-surface echo used to measure the input-pulse frequency, which is 13.4 MHz in this case. The other three images are sections in three orthogonal planes through the amplitude dataset with superimposed locations of the front and back surfaces (red) and the resin layers (green).
3.4 Fibre-tow orientation mapping.

Either Radon transforms (9) or structure tensors (8) can be used to analyse the data in terms of ply out-of-plane angles, from which the displacement of the plies from their expected location can be determined and mapped as a surface height - Figure 4. The wrinkle angle is most significant for strength prediction as shown by Xie et al (4). It is then possible to image the ply wrinkling in 3D, as shown in the top-left image of Figure 4 where the most severe wrinkle in this specimen is illustrated with an exaggerated depth (vertical) axis.

![Figure 4](image.png)

Figure 4. Surface-height measurements for each ply determined from ply out-of-plane angle data from the same specimen as Figure 3. Top-left is a 3D image of a ply at a depth where the wrinkling is most severe, determined from this surface-height dataset.

An example of the Radon-transform measurement of local fibre-tow in-plane orientation is given in Figure 5 in the case where flat horizontal slices are used for analysis. This figure shows that, whilst the stacking sequence can be determined, there is some interference between plies due to the out-of-plane wrinkling. A recent innovation that solves most of this problem with pre-processing that is beyond the scope of this paper, is in preparation for publication. The process involves the use of structure tensors to define locally-orientated sample planes that follow the ply wrinkling (8).
4. Conclusions

In this paper, a process has been described for inverting full-waveform ultrasonic data from composite laminates to reveal internal microstructural details including ply drops, out-of-plane ply wrinkles and in-plane waviness.

The example given of a real aerospace sample, cut from a used component, demonstrates the whole process including the need for pre-processing of the data, conversion to the analytic signal using a Hilbert transform and analysis of the front-surface echo in order to characterise the input pulse. Then plies can be tracked to reveal out-of-plane wrinkling and to map wrinkle characteristics. Finally, structure tensors or Radon transforms can be used to map the in-plane fibre-tow orientations and any in-plane waviness.
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References