Automated Analysis and Advanced Defect Characterisation from Ultrasonic Scans of Composites

NDE Group, QinetiQ Ltd
Cody Technology Park, Farnborough, GU14 0LX, UK
Tel: +44-1252-395655, Fax: +44-1252-393053
E-mail: RASmith@QinetiQ.com Web: http://www.qinetiq.com

Martin J Mienczakowski and Richard E Challis
Applied Ultrasonics Laboratory, School of Electrical and Electronic Engineering,
The University of Nottingham, University Park, Nottingham, NG7 2RD, UK.

Abstract

With the rapidly escalating usage of composite materials, not only in military aircraft but in civil airliners as well, production NDT throughput is already stretched to its limit internationally. NDT data analysis is set to become the bottleneck preventing the required rise in production rates of composite civil aircraft in the next few years. Thus there is an urgent requirement for rapid, automated analysis of up to a Terabyte of data per airliner, escalating to over 200 Terabytes per year - worldwide. The primary aim of automated analysis is to release operators from the time-consuming analysis of all scans and focus operator attention on non-compliant structures. A secondary aim is to provide three-dimensional quantitative information that lightens the operator’s decision-making burden.

Through advanced characterisation methods, NDT also has the potential to provide crucial feedback to control the composite production process, increase production yield and decrease costs. Current analysis methods for ultrasonic scans produce through-thickness average parameters, which provide little useful information to assist the stress analysis for defects, or the production process. Three-dimensional characterisation of defects can increase yield by informing the concession/disposition process for defects. For future process control, information is required about the 3D distribution of material properties in the structures on the production line, providing comprehensive long-term trend analysis.

As well as demonstrating a new rapid automated analysis method for large-area ultrasonic scans, this paper proposes new ultrasonic methods for generating quantitative 3D profiles of porosity, resin layer thickness, ply spacing and fibre orientation. From these it is possible to determine ply stacking sequence and measure in-plane fibre waviness and out-of-plane fibre wrinkling. Armed with these new tools there is the potential for solving the NDT data-analysis bottleneck for composite aircraft. Examples are given of the use of these tools on carbon-fibre composite structures. Stacking sequence has been determined in structures up to 18 mm thick, and out-of-plane wrinkling measured in 35 mm thick structures, although penetration depends on the measurement parameter, material quality and the ply spacing. The tools are software based and are applied through post-processing of full-waveform data.
acquired using one of several suitable ultrasonic acquisition systems. These include commercially available phased-array systems.

1. Introduction

At present the civil aerospace industry is undergoing its most rapid period of change in history, due to the large-scale move from metal to composite primary structures. This poses various challenges for the non-destructive testing (NDT) community, which has, until now, coped with the small amounts of civil-aircraft composite structure by adapting NDT methods used on metals, or by spinning out military NDT methods. The most immediate challenge is on the production line where, initially, every square inch of composite primary structure will be inspected at manufacture.

The long history of composites NDT research in the UK has been covered recently in a review paper(1), including 35 years of research activities at the authors’ organizations. This section provides some more specific background information in two areas: automated analysis and sentencing, and fibre orientation and ply stacking sequence.

1.1 Automated analysis and sentencing

Analysis of large-area data can be accelerated using automated Reference Scan Methodology to perform registration (alignment) in both translation and rotation, followed by comparison with stored reference scan data. The reference scan is intended to represent a ‘perfect’ component and can be either simulated or generated from real scans of nominally identical components. Then the two data sets are compared (see Figure 1) and the resulting differences classified in terms of the cause (structural misalignment, noise, or a defect), and various measurements are performed. These measurements are compared with manufacturer’s acceptance criteria and used to filter out the large amount of data on ‘good’ structure. It is expected that this process could reduce the amount of data needing operator analysis by 90%, depending on the amount of good quality material produced.

![Figure 1. The back-wall amplitude C-scan (left) is registered in translation and rotation with the reference scan (centre) before being compared to produce the right-hand image in QinetiQ’s PinPoint™ software, followed by image comparison to highlight the damage.](image-url)
1.2 Fibre orientation and ply stacking sequence

The original work by the authors on ply stacking sequence, in 1993, was to determine ply stacking sequence non-destructively for a carbon-fibre reinforced plastic (CFRP) skin over a honeycomb sandwich structure(2) – see Figure 2.

Eight years later, Hsu et al at Iowa State University(3) reproduced this original work and then went on to use 2D Fast Fourier Transforms (2D-FFTs) to accurately determine ply orientation for carbon-fibre reinforced plastic (CFRP) – a process that was beyond the computational capabilities of the computer used in 1993. The authors have developed a variant of this 2D-FFT method (Figure 3) and applied it to CFRP structures (Figure 4).

Figure 2. Fiber orientation scans used to determine ply stacking sequence over honeycomb on an in-service structure in 1993. These amplitude C-scans are from successively deeper narrow gates, showing plies at nominal angles (left to right): 135°, 135°/45°, 45°/90°, 90°/0°/135°.

Figure 3. C-scan (top-left) from the second ply interface, 2D FFT (top-right) and (right) angular analysis of ply orientation with peaks at approximately 45° and 135°.
2. Modelling of ultrasonic propagation in composites

A multi-layer ultrasonic bulk wave propagation model, \textit{MLM-Propmat}, has been developed to simulate the reflection and transmission responses of composite materials. Each layer is modelled as an effective medium using conventional mixture rules for the physical properties\cite{4}. These have been augmented to include the frequency dependence of ultrasonic attenuation due to porosity in the resin, based on the scattering theories of Epstein and Carhart\cite{5} and Allegra and Hawley\cite{6}.

The effects of porosity and other panel defects were investigated by using a flexible simulation of ultrasonic wave propagation through multi-layered structures. For the purposes of simulation it was assumed that a monolithic composite could be considered to contain multiple layers which could consist of resin alone, resin with fibres, or either of these with the inclusion of porosity. The model is essentially a transfer matrix formulation, and follows the earlier work of Freemantle\cite{7}. A description of the model was presented recently by Mienczakowski \textit{et al.}\cite{8}. For benchmarking purposes, a different and completely separate model was developed by the authors using similar mixture rules but a different software architecture and the ultrasonic attenuation due to porosity was calculated using the method described by Adler \textit{et al.}\cite{9}. This second model was built into QinetiQ’s ANDSCAN\textsuperscript{®} Waveform Analysis software for easy comparison with experimental data. The ability to compare the two models proved invaluable during this programme.

A comparison between A-scan signals obtained using the models and experimental data indicated that the simulations showed stronger inter-ply resonances than were observed experimentally. A better match between model and experiment was observed when the thicknesses of the layers in the simulated composite were randomised by small variations about their mean values (see Figure 5).
Figure 5. 25 MHz modeled waveforms and corresponding time-frequency plots using different amounts of randomness in the spacing of the 24 composite plies. (left to right) 0%, 8%, 40% randomness. The ANDSCAN-based model was used to simulate these waveforms.

The models have been used in the current programme to develop techniques to detect, localise and characterise flaws in composite materials. For example, Figure 6 shows the waveform and time-frequency plot simulated using the ANDSCAN-based model.

Figure 6. Modelled ultrasonic waveform and time-frequency plot for a 32-ply composite with porosity in ply 10 and thick resin layer at ply 18, 10 MHz probe.
Figure 6 simulates a 32-ply structure (0.125 mm, 0.050” thick plies) with one porous ply (ply 10) and one thick resin layer (just above ply 18), inspected by a 10 MHz probe. It illustrates the markedly different frequency response from porosity and a thick resin layer.

3. **3D characterization of composite material properties**

By consulting composites design engineers and materials scientists, it was possible to generate a list of material properties where accurate 3D measurements would be advantageous: distributed porosity, layer porosity, fibre volume fraction (thick resin layers etc), fibre orientation, ply stacking sequence, in-plane fibre waviness and out-of-plane fibre wrinkling.

Most of the critical material properties for CFRP, such as porosity volume fraction and fibre volume fraction (FVF) are currently measured indirectly using ultrasonic parameters related to bulk properties. Direct measurements of material properties would be of more use to structural designers and process control managers, especially if they could be mapped as a function of 3D location. This would allow structural designers to vary the acceptance criteria on these parameters depending on the predicted stress at each location, resulting ultimately in lighter, less-conservative structures.

Full-waveform acquisition and storage is now becoming commonplace for both production and in-service ultrasonic inspection. From the full-waveform data there is potential for the direct measurement of various important material properties as 3D profiles by analyzing separately each 3D volume element in the structure. The authors are currently collaborating to investigate new ways of decomposing the ultrasonic volume-element response into contributions from the above list of material properties.

### 3.1 Fibre-resin effects

Fibre-resin changes (eg FVF or ply spacing) are not visible in a back-wall echo amplitude C-scan because this parameter is insensitive to such anomalies. An alternative is to look at local changes in ultrasonic response of each volume element, building up a 3D profile like in Figure 7, which can be related to FVF if some assumptions are made about fibre distribution. Changes in FVF at specific depths were created in the specimen by cutting triangles from one pre-preg ply and replacing in a different ply.

### 3.2 Porosity measurement

The requirement to measure porosity content dictates the main acceptance thresholds on bulk ultrasonic attenuation for production inspection of CFRP. Various attempts have been made to improve the quantification of porosity and these have been recently reviewed[10]. In order to develop a new porosity measurement capability it was essential to use the above models to understand how the many factors affect the proposed porosity measurement method. Then a strategy had to be developed to separate or compensating for these effects.
The authors have already produced 3D profiles that qualitatively identify the distribution of porosity in a CFRP structure (see Figure 8), but the aim of the collaboration is to produce quantitative 3D information about porosity, both in production and in-service for repairs.

Figure 8. Sections through a 3D profile of a parameter related to porosity of the panel shown schematically in Figure 7.

3.3 Ply Stacking Sequence

An automated ply stacking sequence tool: StackScan™ has been developed. It provides a rapid method of checking not just the ply stacking sequence at various locations on a structure, but also the exact ply orientations to an accuracy of ±0.5°.

The angular distribution is determined for each depth and is converted to a colour or greyscale horizontal line. These lines are stacked to represent the angular distribution as a function of depth in the structure - see Figure 9.
Figure 9. Ply stacking sequence (centre) determined to 15.5 mm depth, for the structure photographed on the left. Note the good correlation where the sequence deviates from the ideal/design. The stacking sequence on the right is from composite containing sixteen 0.125 mm plies above honeycomb.

Note the good correlation with the photographed corner of the specimen in Figure 9 where the sequence deviates from the ideal.

3.4 Ply Fingerprinting™ of woven fabrics

A further development of the StackScan™ methodology is Ply Fingerprinting™, which applies to woven-fabric materials. The principle is that each weave type (see Figure 10) has a unique fingerprint in terms of angular distribution.

Figure 10. Illustrations of various standard weave patterns: (left to right) plain weave, basket 2x2 weave, twill 2x2 weave, and 4-harness satin weave with a ‘crow’s-foot’ [1,2,3,2] repeat. Images courtesy of Gurit/NetComposites.

A simulated image for a 5 harness-satin weave with a repeat pattern of [2], and its associated angular distribution, are shown in Figure 11. It is expected that peaks would appear at angles of 26.6° (arctangent 1/2), and the 90° offset to this at 116.4°. Both these angles are evident in the angular distribution of the simulated image, but other angles are also present, most notably the strong indication at approximately 73°.
A 10 MHz ultrasonic C-scan from a short time gate in a panel of 5 harness-satin weave is shown in Figure 12, together with the calculated Ply Fingerprint™. Peaks are expected at angles of -26.6° (arctangent -1/2), and the 90°-offset to this at 63.4°, as well as 18.4° (arctangent 1/3) and 108.4°. These angles are seen in Figure 12, with angles 0°, 90° and 126° also present. Deviations from the normal angular distribution could signify shear or stretching of the woven fabric, quantifying the distortion in regions of complex curvature.
Figure 13 shows a stacking sequence for an eight-ply woven fabric where the upper four plies have a different kind of distortion to the lower four plies. Also illustrated diagrammatically are the angles that would result from stretch or shear.

Figure 13. Stacking sequence from an 8-ply woven fabric panel. Angles present in the top plies: -26°, 0°, 20°, 64°, 90°, 110° and the bottom plies: -20°, 0°, 26°, 70°, 90°, 116°.

3.5 In-plane fibre waviness

The 2D-FFT method has been extended to provide a two-dimensional (2D) map of fibre orientation by applying the analysis to a small area in a C-scan, then stepping this analysis region across the image in raster fashion – see Figure 14.

Figure 14. Left to right: A C-scan from a short time-gate at a wavy ply in a pre-preg structure; a quantitative 2D map of fibre orientation; the previous two combined using the scale (right).
3.6 Out-of-plane fibre waviness

A similar 2D-FFT method is being evaluated for detecting and measuring out-of-plane fibre waviness by applying it to B-scan images of ply orientation. This quantitative out-of-plane wrinkling method has been applied to real data in structures as thick as 18 mm (0.750”) - see Figure 15.

![Figure 15. Quantification of out-of-plane wrinkling in a real 72-ply 18-mm thick structure using a 2.25 MHz focused probe. The 2D-FFT method has been applied to the B-scan (left) to produce the quantitative map of fibre orientation (centre) and a combined image is also shown (right). The calibrated scale of ply angle is shown on the far right.](image)

4. Conclusions

This paper has summarized the current status of advanced NDT technology for use in automated defect detection, defect characterization, assessment of concession/disposition and repair strategy for composite production components.

A key proposal is the Reference Scan Methodology, which makes use of the potential to create or simulate a full-structure full-waveform scan of a ‘perfect’ component for future comparison of production components. This will enable the rapid automated analysis and sentencing of large-area ultrasonic data captured during the production process in order to filter the scans of acceptable structure and focus the operators on the potentially defective components.

Advanced 3D materials characterization methods can then be applied to any defect indications in order to provide accurate information about material properties for the purposes of planning repair strategy or concessions (disposition). The provision of 3D profiles of actual material parameters, rather than NDT parameters such as ultrasonic attenuation or velocity, is a significant breakthrough.
The outcome will be a considerable increase in NDT throughput and a more efficient disposition process.

5. Acknowledgements

Elements of this work formed part of a targeted research program of the Research Centre for Non-Destructive Evaluation (RCNDE), UK, funded through the Engineering and Physical Sciences Research Council (EPSRC), UK, and contributing industries, and hence the authors gratefully acknowledge support from Airbus UK. The authors would also like to thank Dr Richard Freemantle of Wavelength NDT for collaboration on the Propmat model and out-of-plane wrinkling, and for feedback on the applications.

References


‘ANDSCAN’ is a Registered Trademark of QinetiQ Ltd.
‘StackScan’, ‘Ply Fingerprinting’ and ‘PinPoint’ are Trademarks of QinetiQ Ltd.
‘MLM-PropMat’ is a Trademark of the University of Nottingham.
Patents have been filed by QinetiQ Ltd covering the technology described in this paper.
© Copyright QinetiQ Ltd. Published in INSIGHT, by permission of QinetiQ Ltd and the University of Nottingham.