Three-dimensional fibre-orientation characterisation in monolithic carbon-fibre composites.

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Abstract
The route to lighter composite aerostructures requires advanced 3D non-destructive characterisation methods to provide confidence that the as-built structures conform to the design expectations. Ultrasound is the ideal vehicle for exploring the local response of a composite structure to stress, and map this across the whole 3D structure. The wavelength, bandwidth and beamwidth can be optimised for just the right sized volume element to characterise plies and fibre tows, whilst providing data that can be inverted to give 3D fibre direction, ply spacing, fibre volume fraction and, in the future, 3D porosity distribution. The first material property that must be determined to enable full characterisation and materials modelling of as-manufactured composite components is the vector field representing the fibre direction at every point. Following an extensive study of the literature for characterising other kinds of fibrous or textured images (fingerprints, hair, textiles, etc) the most promising methods have been evaluated and compared. This paper presents the findings of this evaluation and demonstrates the ability of the optimum method to map in 3D the actual fibre orientations throughout a composite component.

Keywords: Ultrasound, non-destructive characterisation, aerospace, carbon fibre composite

1 Introduction

One of the reasons for current composite aerostructures being only marginal improvements on their metallic counterparts is that additional plies of composite are added to mitigate the risk of unknown deviations from the design. Therefore, the provision of non-destructive characterisation information on conformance to design of as-manufactured components is a feasible route to reduction in thickness, weight, fuel consumption and carbon emissions. With lighter structures comes an increased vulnerability to accidental impact damage in-service, so there will also need to be a change in design strategy to reduce the need for repairs or replacement of vulnerable components.

The most immediate need is for 3D mapping of fibre orientation, including both out-of-plane ply wrinkling in in-plane fibre waviness. This also forms the first requirement for finite-element mesh generation if a structure’s performance is to be modelled. Whilst Micro-CT X-ray imaging has been shown to offer potential for the 3D characterisation of fibre orientation [1] it is not a practical method for many of the critical primary structures on civil aircraft due to their size. In order to achieve sufficient resolution of fibre orientations, the specimen must be orders of magnitude smaller than many of these components. Ultrasound, however, is ideally suited to 3D characterisation of composites because it can be scanned over large areas, the ply thicknesses lie in the range of wavelengths available and the variations due to fibre tow widths can be imaged using beamwidths achievable with standard NDT focused-ultrasound beams. It has been demonstrated that in-plane fibre orientation can be imaged, measured and mapped due to the imprint of the fibre tows on in-plane (C-scan) cross-sections of 3D full-waveform scans [2-4]. Out-of-plane ply wrinkling can also be detected, measured and mapped from B-scan slices through this full-waveform 3D data [4] – see Figure 1. The methods used in these publications were based on an automated angular analysis of two-dimensional fast Fourier transforms (2D-FFT) of small overlapping portions of B-scan and C-scan slices through the data. Whilst the method worked, there had been no systematic study of the numerous other fields where orientations of lines in two-dimensional images have to be determined, so it was unclear whether this 2D-FFT method was optimum. The paper
addresses this issue by comparing three methods for mapping local orientation in pursuit of 3D fibre orientation measurement.

Figure 1. Diagram explaining the capture of a 3D ultrasonic full-waveform data set (top) and the three cross-sectional planes that can be used for analysing fibre orientation.

2 Two-dimensional angle measurements

It is possible to calculate the three-dimensional orientation of fibres from angular measurements in the three two-dimensional cross-sectional planes through the data (Figure 1). The two B-scan cross-sections give information about the out-of-plane ply angles (α and β), which are sufficient to define the local plane of a ply – see Figure 2. α and β can be used to describe two unit vectors \( \mathbf{1} \) and \( \mathbf{2} \) which lie in both this ‘ply’ plane and the y-z and x-z planes respectively – see Figure 2.

A unit vector \( \mathbf{3} \) is then determined as a cross product of \( \mathbf{1} \) and \( \mathbf{2} \) and is orthogonal to the ply.
Finally, the in-plane fibre angle, $\gamma$, is used to find a unit vector $\mathbf{F}$, in line with the fibres, see Figure 2.

\[
\mathbf{F} = \begin{pmatrix}
\cos \theta_f \cos \gamma \\
\cos \theta_f \sin \gamma \\
\sin \theta_f
\end{pmatrix}
\]

where:

\[
\tan \theta_f = \cos \gamma \tan \alpha + \sin \gamma \tan \beta
\]

Numerous methods exist for detecting lines in two-dimensional images and measuring their angle. The critical requirement here is an accurate angular measurement from a small local segment of the image. In the 2D-FFT method mentioned above, and in most other methods, the angular accuracy improves with an increasing number of pixels in the segment [5] for two reasons: the line lengths increase so that their angles become better defined; the number of parallel lines in the segment increases with area. An optimum image analysis method would be able to determine the local line angle from a very small segment of the image.

### 2.1 Image gradient methods

There is a whole family of methods for determining dominant angles in images based on local image gradient (derivative) measurement. Much of this work has been aimed at parameterisation and classification of fingerprints for biometrics, forensics and security [6,7] – see Figure 3(a). The vector representing the maximum image gradient is assumed to be perpendicular to a local line (or ridge) in a segment of two-dimensional image data. The simplest of these methods use kernel (matrix) operators.

Sobel operators (or filters) are two 3x3 kernels, which determine the gradients with smoothing, $G_x$ and $G_y$, parallel to the horizontal (x) and vertical (y) axes respectively [8]. The gradient magnitude $G$, and direction $\theta$, are then given by:

\[
G = \sqrt{G_x^2 + G_y^2} \\
\tan \theta = \frac{G_y}{G_x}
\]

As Sobel operators are just 3x3 matrices, they are very local in influence and quick to compute, but are rather crude in approximating the gradient and do not have perfect rotational symmetry. Scharr operators, however, are optimised for rotational symmetry in a range of kernel sizes and optimised versions can be calculated [9]. Several other operators such as Prewitt [10] have been developed using similar principles but attempt to have higher accuracy whilst still using a small segment of the image.

In 1986, Canny [11] developed a new edge-detection process known now as the Canny algorithm, which incorporates noise reduction via a Gaussian filter combined with a rough calculation of image gradient magnitude and direction, using one of the above operators. This is used to categorise the gradient into one of eight directional sectors and check that the calculation is not suffering from local noise. This method can also calculate gradients and is used by Nikishkov et al [1] for interpreting X-ray CT images of wrinkling in composites.

An extension of this image-gradient principle is the structure tensor [12]. In two dimensions this comprises not just the gradients $G_x$ and $G_y$, parallel to the horizontal (x) and vertical (y) axes, but also information about the degree to which these directions are coherent. The
structure tensor has eigenvalues and corresponding eigenvectors that summarise the distribution of the gradient measurements within the segment of the image including the dominant direction, represented by the eigenvector with the largest eigenvalue. The coherence is a measure of how strongly the gradient is biased to a particular direction. A three-dimensional structure tensor can be used to determine the dominant direction of tubes or rods through a 3D data set. This could be appropriate for fibre tows in a composite.

Figure 3. Example images from fields in which computation of local orientation is a requirement. (a) Fingerprint enhancement [7], (b) digital hair modelling [15]. Also, (c) a two-dimensional spatial Gabor filter [13-16].

2.2 Rotated periodic filters
Another kind of filter for determining directions of lines in 2D images is a Gabor filter (see Figure 3(c)) [13-16]. This is a Gaussian kernel function multiplied by a sinusoidal plane wave. These filters are used in sets which cover a complete range of angles and are intended to find the dominant angle of a particular wavelength of undulations in the image. The main application has been for classifying and measuring the waviness and tones of human hair in images [15] — see Figure 3(b). Whilst the angular discrimination of Gabor filters is good, the need to know the best wavelength of the sine wave is a disadvantage.

The principle is that each of the Gabor kernel filters in the set is applied and the angle of sine-wave that produces the maximum product is the angle of the lines in the image. However, these methods tend to be slow and, where speed is important [16], more efficient gradient methods [17] are preferred. A refinement stage is necessary among both orientated filter and gradient techniques to improve the initial orientation field estimate. Diffusing results from high confidence regions to suppress noise in low confidence regions is a common technique [18]. Additionally, one may use intuitive properties of the orientation field (for example high-confidence pixels are more likely to have a high-confidence neighbourhood along the estimated orientation than pixels with a false-positive high confidence) to remove spurious results and perform iterative refinement [15, 19]. A final technique is to use a multi-scale analysis whereby low confidence pixels are populated by results from orientation fields obtained at a coarser or finer scale [20].

2.3 Radon Transforms
There is a class of techniques which perform an image transform in order to reveal orientation information. A commonly used transform for this purpose is the Radon transform and this is particularly appropriate for images of fibre tows in in-plane C-scan slices through the ultrasonic data. The Radon transform in two dimensions comprises an integral of the image along straight lines, each defined by an angle and distance from the image centre. It was introduced in 1917 by the Austrian mathematician Johann Radon [22, 23]. Although widely used in the reconstruction of CT data, where the transformed image is known as a sinogram, it
has also found uses for the detection of orientated features in 2D images. For example, Figure 4 shows an image of aligned fibres, and its Radon transform. The high spatial-frequency perturbations at approximately 135º are attributed to the alignment of the fibres at that angle. Of critical importance in using the Radon transform to detect fibre orientation is the reduction of the transform to a 1D angular probability density function (PDF). One algorithm calculates the variance in the Radon transform image for each angle, to find the PDF [24]; the predominant orientation is assumed to have the highest variance. However, care must be taken to avoid low-frequency features in the image that can contribute to the variance, so the analysis was often applied to a disc-shaped area of the texture image [24].

![Figure 4](image)

Figure 4. A 2D image of aligned fibres (A), and the Radon transform (B). From [25].

An algorithm having less sensitivity to low-frequency features than the variance takes the sum of the absolute value of the first derivative of the Radon transform in the radial direction (vertical axis in Figure 4B) [25]. It is also possible to improve the angular PDF by pre-processing an image using, for example, gradient filters to enhance edge features [26].

### 3 Assessment of angle-measurement methods

In order to compare the various methods mentioned above for determining local angles of lines in typical ultrasonic horizontal slice (C-scan) images, standard simulated images were used, with 1 mm mean line spacing and a sine-wave wrinkle (Figure 5).

![Figure 5](image)

Figure 5. Simulated images using 1 mm mean spacing of zero-degree lines with a 3 mm amplitude, 20 mm wavelength wrinkle modulated by a Gaussian envelope with a 1/e half-width of 8 mm. Image (a) defines the lines by 1 mm wavelength sinusoidal oscillations; image (b) includes randomised amplitudes of sub-harmonic wavelengths (multiples of 1 mm); image (c) is as (b) but with 30% ‘noise’. The pixel size is 0.2 mm.

The wrinkle was modulated with a Gaussian envelope and is given by the following equation for the y-direction displacement, \( \Delta y \) as a function of the x-coordinate position:

\[
\Delta y = -A e^{-(x-x_0)^2/\sigma^2} \sin\frac{2\pi(x-x_0)}{\lambda}
\]  

where \( A \) is the amplitude (3 mm), \( \lambda \) is the wavelength (20 mm), \( \sigma \) is the 1/e half-width of the Gaussian envelope (8 mm) and \( x_0 \) is the location of zero phase and the peak of the Gaussian envelope (19.5 mm). The difference between the two simulated images is that Figure 5(a) has lines created with sinusoidal amplitude variations (Equation 6). Figure 5(b) has a more realistic line-creation method with additional sub-harmonics of randomised amplitude to produce an image that better simulates an in-plane slice through a full-waveform ultrasonic
data set from a composite specimen. Figure 5(c) has $\delta=30\%$ additional noise, $\varphi$ added as random additional phases at each pixel (Equation 6) corresponding to a flat distribution of $\varphi$ in the range from $-\delta\pi$ to $+\delta\pi$. The sinusoidal fibre-tow amplitudes are given by the following equation for the grey level, $g$ as a function of the y-axis coordinate:

$$g = g_{\text{offset}} + g_0 \sin\left(\frac{2\pi y}{w} + \varphi\right)$$

(6)

where $w$ is the fibre-tow width, $g_{\text{offset}}$ is the grey level about which the fibre-tow images are centred (128 for an 8-bit image), $g_0$ is the amplitude of the grey-level oscillation (100 in this case), and $\varphi$ is an additional phase term to allow simulation of noise. In addition, other simulated and real images have been used to investigate specific characteristics of the angle-measurement methods. For example, a 2 mm line spacing was used to investigate whether the optimum filter kernel size depends more on fibre-tow spacing or wrinkle wavelength.

The analysis was performed using a square kernel, which was moved in raster fashion across the images, with 75% overlap of adjacent locations. In each of the following graphs, the measured angles are plotted for comparison with the ‘simulated’ angles, $\gamma$, based on calculation of the local gradient, $dy/dx$, of Equation (5), as follows:

$$\tan \gamma = \frac{dy}{dx} = 2Ae^{-\frac{(x-x_0)^2}{\sigma^2}} \left[ \frac{(x-x_0)}{\sigma^2} \sin \frac{2\pi(x-x_0)}{\lambda} - \frac{\pi}{\lambda} \cos \frac{2\pi(x-x_0)}{\lambda} \right]$$

(7)

Finally, after the dominant angle had been determined for each kernel location, a Gaussian weighted-mean smoothing algorithm was applied over the size of the kernel, thus encompassing 16 angle measurements due to the 75% overlap – i.e. a step of 25% of the kernel size. The smoothing algorithm was applied to the sine and the cosine of the angles – avoiding errors due to the distribution of angles straddling the $\pm\pi$ wrapping point of the $\text{atan2}$ function.

The gradient, rotated periodic filter and Radon transform methods were tested using simulated images of 1 mm spaced fibre-tows (Figure 5), with (a) sinusoidal and (b) randomised amplitude variations. The dependence on kernel size is shown for the image-gradient (Canny operator) method in Figure 6 with colour images of measured angle in two specific cases. Larger kernels (>3 mm) gave much larger errors and could not be plotted meaningfully.

![Figure 6. Canny-operator analysis of 1 mm fibre tows simulated using a sinusoidal amplitude variation - Figure 5(a). Inset - Canny filtering analysis (colour) with simulated C-scan, using sinusoidal fibre-tow amplitude variations, superimposed in greyscale. Analysis kernels were squares of width 1 mm (left), and 3 mm (right).](image-url)
For random fibre-tow amplitudes, the image-gradient (Canny) method performed considerably better (Figure 7) for larger kernel sizes. The same image has been analysed using 1 mm periodicity Gabor operators (Figure 8), and Radon transforms (Figure 9). For the Radon transform method, the angular PDF was formed using the variance of the first derivative of the Radon transform with respect to distance of a line from the origin.

Figure 7. Gradient (Canny operator) analysis of 1 mm spaced fibre tows with a random amplitude variation - Figure 5(b). Inset image is the result of the 3 mm-square analysis kernel.

Figure 8. Rotated periodic filter (1 mm periodicity Gabor) analysis of 1mm spaced fibre tows with a random amplitude variation - Figure 5(b). Inset image is the result of the 3 mm-square analysis kernel.

Figure 9. Radon transform analysis of simulated 1 mm fibre tows with a random amplitude variation - Figure 5(b). Inset images are the result of the 1 mm (left) and 3 mm (right) analysis kernels.
4 Comparison of methods

A summary of the trends in maximum error in angle measurement can be found in Figure 10. Image-gradient (Canny) operators appear less tolerant of analysis kernel size than periodic filter (Gabor) operators matched to the dominant periodicity or Radon transform methods. An analysis kernel size of two to three times the fibre-tow spacing appears to be optimum for a wrinkle wavelength of 20 times this spacing.

A random uncertainty exists when the measurement of angle is not repeatable from one measurement to another in the same conditions. For example, incoherent noise in the image will have a different effect on each measurement of a given angle, depending on the local noise. This was assessed by adding random phase shifts in the range $-\delta\pi$ to $+\delta\pi$, where $\delta$ is expressed as a percentage (see Equation 6), to the fibre-tow images, and an example is shown in Figure 5(c). The random uncertainty can be quantified and assessed by plotting the standard deviation in measured angle as a function of simulated angle, for different noise levels. Such graphs, for noise levels ($\delta$) from 0 to 40%, are shown for the image-gradient (Canny-operator) method in Figure 11, the rotated filter (Gabor-operator) method in Figure 12 and the Radon transform method in Figure 13, using a 2 mm analysis segment size in each case.

Figure 10. Trends in maximum angular error in the mean measurement of angle as a function of analysis kernel size for sinusoidal (left) and random (right) fibre-tow amplitude variations.

Figure 11. Image gradient (Canny-operator) method: Standard deviation in measured angle as a function of simulated angle for noise levels, $\delta$, of 0%, 10%, 20%, 30% and 40%.
The Gabor operator (Figure 12) shows a considerable difference in standard deviation for the same angles when at a positive y-deviation of the waviness compared with the negative y-deviation. This is thought to be due to the different curvatures in those regions of rapidly changing angle. For the Radon transform (Figure 13), the two lines approximating the trends in uncertainty show a standard deviation of $0.25^\circ \pm 0.05|\gamma|$ or an uncertainty of $0.25^\circ + 5\%$.

Finally, a real 3D ultrasonic data set from a specimen with a stacking sequence described as: $[45, 0, -45, 90, -45, 0, 45]_3$ was analysed for in-plane local fibre-tow orientation using the
three methods described. The results (Figure 14) are shown as B-scan and C-scan cross sections (upper image and lower image respectively). The C-scan is from plies 7 and 8 which have a 45-degree fibre orientation. Also shown is a B-scan and C-scan cross-section of the original ultrasonic data, with the C-scan being a mean of all the depths corresponding to the +45° plies in question (plies 7 and 8). The conclusion drawn from this comparison is that the reality of data acquired on a real composite specimen considerably reduces confidence in the measured results, particularly for the image-gradient and rotated periodic filter methods (Canny and Gabor respectively), but that confidence in the Radon transform is enhanced. It is thought that the small size (2 mm) of the analysis segment used tends to exaggerate the small local perturbations in the lines of the image. Also, despite the averaging across multiple depths in the scan, there is still an impression of some of the features of the ply above and the ply below, especially at the right-hand edge of the scanned area of the specimen. The range of angles is limited to ±60° around the dominant angle in a ply so encroaching adjacent plies are not measured accurately.

5 Conclusions

This paper reports a comparative study into processing methods for determining local fibre-tow orientation in two-dimensional images but is ultimately aimed at implementation in three dimensions. The three methods investigated were: image-gradient methods, represented by Canny operators, rotated periodic filters, represented by Gabor operators, and the Radon transform method using the variance of the first derivative to convert to an angular dependence.

Systematic studies using simulated images showed that periodic filter (Gabor) operators and Radon transform methods are more tolerant of analysis kernel size than image-gradient (Canny) operators. Also, an analysis kernel size of two to three times the fibre-tow spacing appears to be optimum for a wrinkle wavelength of 20 times this spacing.
Trials with real ultrasonic full-waveform data showed that the Radon transform method produces angle-measurement maps that are more consistent with the original image than either the Canny or Gabor operators.

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References


