An Active Infrared Thermography Method for Fiber Orientation Assessment of Fiber-Reinforced Composite Materials

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Abstract

Fiber orientation in composite materials is an important feature since the arrangement or orientation of the fibers relative to one another has a significant influence on the strength and other properties of fiber reinforced composites. In this paper we present a method to assess the fiber orientation on the surface of carbon fiber reinforced polymer (CFRP) laminates. More specifically, a diode-laser beam is used to locally heat a small spot on the surface of the sample. Observation of the heat pattern in the infrared spectrum enables the assessment of the fiber orientation. Different samples and different regions on the surface of the samples are tested in order to estimate the precision of the method.

Keywords: fiber orientation assessment, infrared thermography, non-destructive testing, composite materials, carbon fiber reinforced polymer

1. Introduction

Composite materials are widely used in the aeronautic industry. One of the reasons is because of they have strength and stiffness comparable to metals with the added advantage of significant weight reduction. Fiber orientation, concentration and distribution have a significant influence on the strength and stiffness
of fiber reinforced composites and consequently must follow some quality standards in order to ensure that they will not fail during their lifetime. Thus, it is important to develop inspection techniques to assess fiber content. Destructive methods can be employed to evaluate the fiber on a composite, e.g. cutting a section of the material, polishing the area and evaluating it with microscopy. However, the destructive approach is not always an option since the sample will be damaged after inspection and probably unfit for use. Thus, Non-Destructive Testing and Evaluation (NDT&E) techniques must be employed in some cases to assess the material’s fiber content.

Infrared Thermography (IT) is a NDT&E technique which is widely used for diagnostics and motoring in several areas including composite materials. Some of the reasons for its popularity are that it is a safe technique, usually contactless and has a fast inspection rate. In active IT an external heat source is used to stimulate the material being inspected in order to generate a thermal contrast between the feature of interest and the background. The active approach is adopted in many cases given that the inspected parts are usually in equilibrium with the surroundings [1].

In this paper, IT is used in order to assess fiber orientation on the surface of carbon fiber reinforced polymer (CFRP) laminates. More specifically, a pulse laser heating technique known as Pulsed Thermal Ellipsometry is used to locally spot heat a region on the surface of the sample. If the material has an oriented structure (i.e. fibers orientated in one direction) with anisotropic thermal properties, an elliptical pattern will be observed. The fiber orientation in this case is the same direction of the ellipse’s major axis. The heating and cooling down profiles are recorded using an infrared camera. The steps required to extract the local fiber orientation from the infrared sequence are presented in this paper. Additionally, tests of several points on different CFRP laminate samples were performed in order to estimate the precision of the method.

This paper is organized as follows: the next section presents the material and methods including a brief literature review on PTE and the proposed method to extract the fiber orientation from a PTE inspection; in section 3 results obtained
are presented and in section 4 they are discussed; finally our conclusions are presented in section 5.

2. Material and methods

2.1. Pulsed Thermal Ellipsometry - PTE

More than one century ago, De Senarmont [2] applied a thermal approach to determine the principal orientations in crystal plates: he covered them with a thin layer of wax, heated them over a small spot and monitored the isotherm shape revealed by the solid/liquid transition contour appearing in the wax layer. The isotherm proved to be elliptical and its aspect ratio is related to the square root of the principal conductivities in the surface plane.

This method, referred to later by Krapez et al. [3, 4, 5, 6] as “Thermal Ellipsometry”, was later used for various applications (with, of course, up-to-date experimental equipment) by means of thermography. It was applied on polymer materials to establish a correlation between their draw ratio and the induced thermal anisotropy. It was also used to evaluate the fiber orientation in the case of composite materials using short or long carbon fibers. For the latter problem, authors like Aindow et al. [7] and Cielo et al. [8] showed that heat propagates faster in the longitudinal direction of fiber on the surface of fiber reinforced laminates. In [7], Aindow et al. detected local anisotropy in CFRP (nylon-66) injection mouldings by two methods: thermography using infrared scanning, which reveals anisotropy of thermal conductivity, and polarized shear-wave ultrasonic showing elastic anisotropy. For the thermographic method, they recorded isotherms formed around a point source of heat on a plane surface (heat was applied for a period of 15 seconds) using an infrared imaging camera. The isotherms that they observed were ellipses of which the ratio of lengths of the principal axes (b/a) are proportional to the square root of the ratio of thermal conductivities. They assumed that the longest dimension of the counter in each picture indicated the major axis of thermal conductivity in the surface, which in turn is related to the direction of fiber orientation.
Cielo et al. presented in [8] a comparative review of a number of optical techniques for the characterization of non-metallic materials. One possibility reported by them is the evaluation of phase (or fiber) orientation in stretched polymer films or in composites by an analysis of the thermal propagation pattern. They spot-heated the inspected part by a narrow laser beam and the resulting heat-propagation pattern was analyzed by an IR camera. If the material is oriented, such as the unidirectional graphite-epoxy sheet they inspected, an elliptical thermal pattern is observed, with the ratio between the two principal axes (b/a) being related to the square root of the thermal conductivities in the longitudinal and transverse directions. A test on an isotropic material would give a circle instead of an ellipse. They illustrated this approach showing results from two 8-ply unidirectional NARMGO 5217 sheets spot heated for a period of 20 seconds with a 0.5 W laser. A typical set-up used in PTE inspection is showed in Figure 1.

A more detailed theoretical analysis was later undertaken through an analytical treatment of thermal diffusion in laminates made of orthotropic layers assuming the surface is submitted to concentrated heating by Krapez in [3]. Three temporal regimes were considered in that study: steady-state regime, transient regime (as obtained during step heating), and modulated regime (in order to analyze how the so-called thermal waves “propagate” in orthotropic laminates).

Figure 1: PTE experimental set-up.
Experiments were performed on carbon-epoxy laminates for all three regimes. In [4], Krapez used the same theory (thermal anisotropy measurements method which consists in analyzing the shape of the isotherms which develop around a heated spot) to develop a thermal inversion method to infer thickness of skin and core layers of a 3-layer carbon/epoxy laminate.

In our previous work [9], as in Karpen et al. [10], lock-in thermography (harmonic thermal waves) is used to probe orientation fields of carbon fibers both along the surface and in depth at low modulation frequencies and within a short time. Later Karpen et al. [11] developed a theoretical model in order to correctly interpret their measurements.

2.2. Image processing technique

After the sample is spot-heated and the temperature profile of heating and cooling down process is recorded, the infrared sequence is stored in a 3D matrix M for post-processing. The matrix M is composed of k images of the size m x n. The number of images depends on the acquisition rate of the infrared camera used in the acquisition and on the duration of the acquisition. The processing steps in order to obtain the fiber orientation from the acquisition sequence can be divided in three: selection of the optimal diffusion time, binary shape segmentation and extraction of the ellipse’s orientation. Figure 2 shows a summary of these steps which are described next.

![Image segmentation processing steps](image.png)

**Figure 2:** Image segmentation processing steps.
2.2.1. Optimal diffusion time selection

The result of a PTE inspection is a sequence of infrared images which contains: the plate before heating, the moment when the beam heated the plate, the rise of the temperature profile and finally the temperature profile decrease. In the case of CFRP which are thermally anisotropic, the heat pulse will produce an elliptical pattern on the surface of the sample. The ellipse major axis orientation indicates which direction has the larger thermal conductivity and since the thermal conductivity along the fibers is always larger than the one perpendicular to it, the orientation of the major axis of the ellipse will be the same as that of the fibers.

The thermal pattern is closer to a circle in the images just after the pulse. Shortly after it becomes an ellipse and as time elapses the ellipse become closer to a circle again due to the influence of deeper layers and heat diffusion through thickness and not only on the surface. Thus, in order to assess the fiber orientation on the surface, an image from an early time when the conductivities of the surface are playing a stronger role must be selected. However, this time must not be too early. If a very early image is selected the heat would not have diffused enough on the surface of the plate and consequently the influence of the larger thermal conductivity alongside the fibers will not be strong enough to assess the fiber orientation. Thus, if one extracts the thermal pattern shape of each image on the infrared sequence, one could easily observe that the major axis orientation of some of these patterns will be very close to the real fiber orientation while others will not.

A fair assumption that could be made is that the pattern that better represents the fiber orientation on the surface would be the one which has the larger rate between the ellipse’s major axis and its minor axis, i.e. the pattern that is ‘the most elliptical’. This concept can be abstracted from the definition of the eccentricity of a conic section. Eccentricity ($\varepsilon$) is a quantity defined for a conic section which can be given in terms of major and minor axes. In the case of a circle $\varepsilon = 0$ while in the case of an ellipse $0 < \varepsilon < 1$. Based on this idea the
thermal pattern that would better express the fiber orientation is the one with the largest $\varepsilon$.

As discussed before, this optimal diffusion time will be located in the beginning of the thermal sequence. Thus, the thermal pattern of each one of the first 100 images (about 0.5 second) is extracted and their eccentricity ($\varepsilon$) calculated. Then, the image with the largest eccentricity value is selected and this image will be used for the segmentation of the binary ellipse from which the fiber orientation of the surface will be extracted later. Figure 3 shows the plot of eccentricity values calculated for each one of the images (of a single inspection) within the first second through time. As it can be observed, the largest $\varepsilon$ occurs in the early times. During our experiments it always occurred before 0.5 seconds.

2.2.2. Binary shape segmentation

After the image with the optimal diffusion time is selected based on the thermal pattern with the largest eccentricity value, the next step is to segment, or binarize, the ellipse on the image. This is a simple task that can be accomplished by using automatic clustering based image thresholding method. There is a wide range of histogram based algorithms for automatic threshold selec-
tion for bimodal and multimodal images available [12, 13]. In this work three different methods are tested: Otsu’s method [14], the valley-emphasis method [15, 16] and Rosin’s method [17]. These methods are briefly summarized next.

The first method is a common thresholding algorithm that was proposed by Otsu [14]. The algorithm assumes that the image contains two classes of pixels following bimodal histogram (foreground pixels and background pixels), it then calculates the optimum threshold separating the two classes so that their combined spread (intraclass variance) is minimal. The second method, the valley-emphasis method, was proposed by Ng [15] as an improvement of the Otsu’s method. In his method the threshold is selected in such a way that it has a small probability of occurrence (valley in the histogram) which maximizes the between class variance, i.e. minimize the variance inside each class, as in Otsu’s method. The last method was proposed by Rosin [17]. It assumes that there is one dominant population in the image that produces one main peak located at the lower end of the histogram relative to the secondary population. A straight line is drawn from the peak to the high end of the histogram. The threshold point is selected as the point on the histogram curve that maximises the perpendicular distance between the line and the point on the histogram. Interested readers may find more details about these methods in the references provided for each method.

After the selection of the threshold level (via any of the methods) the binary image is created by applying the following function of belongingness in the infrared image selected based on the optimal diffusion time calculated in the previous step:

\[
fbe(P_{Ti}) = \begin{cases} 
1, & \text{if } T_i \geq Th \\
0, & \text{otherwise}
\end{cases}
\]  

where \(i \in [1, \ldots, m x n]\), \(m x n\) is the number of pixels in the image and Th is the temperature threshold value determined by one of the three optimal threshold selection methods.
2.2.3. **Ellipse orientation extraction**

With the resulting binary image obtained via Equation 1, which is represented by a binary matrix, Matlab\textsuperscript{\textcopyright} native function `regionprops` was used to calculate the ellipse orientation. The orientation of the image, here the binary ellipse, is the angle (in degrees ranging from $-90^\circ$ to $90^\circ$) between the x-axis and the major axis of the ellipse that has the same second-moments as the region. Figure 4 illustrates the axes and orientation of the ellipse. The left side of the figure shows a small image region of four pixels and its corresponding ellipse in red. The right side shows the same ellipse with its major and minor axes. The orientation is the angle between the horizontal dotted line (x-axis) and the major axis.

2.3. **Inspected laminates and experimental set-up**

In order to assess the performance of the described method, three different CFRP flat laminates were inspected. The first, CFRP001, is a 50 x 50 mm laminate with 48 plies whose layup was $[90/0]_{24}$; the second, CFRP002, is a 100 x 100 mm laminate with 24 plies whose layup was $[90/0]_{12}$ and the last one, CFRP003, is a 100 x 100 mm laminate with 24 plies whose layup was $[90_2/0_2]_{16}$. For all three samples the nominal fiber orientation on the surface was $90^\circ$. For CFRP001 eight different spots were inspected while for the other two laminates twelve different spots were inspected. Each spot was inspected five times. Thus, a total of 160 inspections were performed. A waiting time of 3 minutes was respected between each inspection. Figure 5 shows the inspected samples.

The samples were inspected by PTE using a diode-laser beam spot as stim-
ulation source. The samples were placed, one at a time, in front of the laser beam and a plano-convex lens was placed between the laser beam and laminate (see Figure 1). The lens was used to focus the beam into a small spot on the surface of the laminate (about 2 mm in diameter). The angle of incidence of the laser beam with the plate’s surface, i.e. the angle between the incident beam on the surface and the line perpendicular to the surface at the point of incidence, was about 15° while the camera’s optical axis angle of incidence was 0°, i.e. the angle between the camera optical axis and the plate’s normal to the surface.

The case where the laser beam angle of incidence on the plate’s surface is not 0° was studied in our previous work [19]. It is clear that if the angle of incidence is greater than 0°, the initial shape of the excitation point on the plate’s surface would not be a circle but an ellipsoid and it would distort the evaluation method. In [19] tests were performed with a laminate with known fiber orientation and it was shown that only laser beam angles of incidence greater than ±45° will prevent the application of the PTE technique. With angles of incidence less than ±45° the technique is still feasible and fiber orientation measurements would be, in the worst case, just a couple of degrees off.

A short pulse of 0.1 s was shot heating a small circle area on the plate’s surface. Then, the heating and cooling down process were recorded using a mid-wave infrared (MWIR) camera (FLIR Phoenix, InSb, 3-5 µm). As mentioned before, the pattern formed on the plate’s surface is elliptical in anisotropic materials, which is the case of CFRP composites and the ellipse major axis is
related to the fiber orientation. The parameters used in this experiment are listed in Table 1.

### Table 1: Parameters used during the inspections.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode-laser frequency</td>
<td>805 nm</td>
</tr>
<tr>
<td>Diode-laser power</td>
<td>1 W of 30 W</td>
</tr>
<tr>
<td>Shooting duration</td>
<td>0.1 seconds</td>
</tr>
<tr>
<td>Spot size on plate’s surface</td>
<td>2 mm</td>
</tr>
<tr>
<td>Acquired frames</td>
<td>1200 frames</td>
</tr>
<tr>
<td>Camera’s acquisition rate</td>
<td>220 Hz</td>
</tr>
<tr>
<td>Camera’s frame size</td>
<td>320 x 256 pixels</td>
</tr>
</tbody>
</table>

### 3. Results

After all 160 inspections were performed and data stored for each individual inspection, the infrared sequences were processed according to what was described in section 2. First, the optimal diffusion time was calculated based on the largest eccentricity value and the image corresponding to this time selected. Then, the thermal pattern (an ellipse) was segmented from these images based on the automatic optimal threshold selected. This segmentation was performed with each of the different methods for automatic image thresholding described: Otsu’s method, Rosin method and the valley emphasis method. Then, for each one of the inspections the fiber orientation was determined. In the end, the mean orientation of the data set was calculated as well as the standard deviation (STD) and standard error in order to compare the methods.

With the goal to decrease the error, a variation of the original Otsu’s method was applied. In this variation instead of calculating a threshold that segments the image into two classes, multiple thresholds were calculated that segment the image in more than two classes. In this case, 3, 4, 5 and 6 classes were tested. An example of the segmentation using the Otsus’s method for 5 classes of an
An infrared image containing an ellipse is presented in Figure 6 (corresponding to the first inspection of the first point of sample CFRP001). Figure 6a shows the normalized infrared image (pixel value $\in [0 \ldots 1]$) where the optimal diffusion time used was 0.07 s (Figure 3 shows the plot of eccentricity values through time for the same inspection). Figure 6b shows the corresponding classes segmented using Otsu’s method for 5 classes. By visually observing the results it was decided to consider the second class, which corresponds in the image to the largest ellipse, as the class from which the ellipse (and fiber orientation) will be calculated in the case of multiple thresholds.

Results obtained with Otsu’s method, Rosin’s method, valley emphasis method and Otsu’s method for 3, 4, 5 and 6 classes are presented in Table 2. The image from which the ellipse is segmented in this case was selected by the approach proposed in this work, i.e. based on the largest eccentricity. The second column presents the mean orientation calculated form all 160 inspections for each one of the tested automatic thresholding selection methods. The third and fourth column show the standard deviation and standard error calculated for each case. The last two columns indicate the mean optimal diffusion time calculated based on the largest eccentricity and the mean threshold value calculated for each case.
Figure 7: Normalized infrared image and result of segmentation using different methods. (a-b) Otsu’s method, (c-d) Rosin’s method, (e-f) Valley emphasis method, (g-h) Otsu’s method for 3 classes, (i-j) Otsu’s method for 4 classes, (k-l) Otsu’s method for 5 classes and (m-n) Otsu’s method for 6 classes.

Figure 7 shows the resulting images obtained with the different segmentation methods for one single inspection (first inspection of the first point of sample CFRP001). Figure 7a and figure 7b show the result obtained with the original Otsu’s method. Figure 7a shows the normalized infrared image. The dotted red
Table 2: Result of fiber orientation assessment using different methods for automatic threshold selection.

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean ori.</th>
<th>STD</th>
<th>Error</th>
<th>Mean diff. time</th>
<th>Mean th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Otsu</td>
<td>89.85°</td>
<td>5.86°</td>
<td>0.46°</td>
<td>0.15 seconds</td>
<td>0.24</td>
</tr>
<tr>
<td>Rosin</td>
<td>90.52°</td>
<td>4.33°</td>
<td>0.34°</td>
<td>0.18 seconds</td>
<td>0.03</td>
</tr>
<tr>
<td>Valley emphasis</td>
<td>90.7°</td>
<td>7.31°</td>
<td>0.58°</td>
<td>0.17 seconds</td>
<td>0.31</td>
</tr>
<tr>
<td>Otsu (3 classes)</td>
<td>90.06°</td>
<td>4.79°</td>
<td>0.38°</td>
<td>0.13 seconds</td>
<td>0.12</td>
</tr>
<tr>
<td>Otsu (4 classes)</td>
<td>90.42°</td>
<td>4.3°</td>
<td>0.34°</td>
<td>0.12 seconds</td>
<td>0.11</td>
</tr>
<tr>
<td>Otsu (5 classes)</td>
<td>90.62°</td>
<td>3.99°</td>
<td>0.31°</td>
<td>0.12 seconds</td>
<td>0.09</td>
</tr>
<tr>
<td>Otsu (6 classes)</td>
<td>89.93°</td>
<td>4.17°</td>
<td>0.33°</td>
<td>0.12 seconds</td>
<td>0.08</td>
</tr>
</tbody>
</table>

ellipse shows the boundaries of the segmented ellipse while the white line is the major axis of this ellipse. Figure 7b shows the binarized image containing the segmented ellipse that was used to calculate the fiber orientation. The dotted red line also shows the boundaries of the segmented pattern and the blue line connecting its two extremities represents its major axis. The reaming results in Figure 7 are presented in the same way. Figure 7c and figure 7d show the segmentation obtained with the Rosin’s method while Figure 7e and figure 7f show the segmentation obtained with the valley emphasis method. Figure 7g to figure 7n show the segmentations obtained with Otsu’s method for 3, 4, 5 and 6 classes respectively.

A second round of tests were performed. For these tests the segmentation method was fixed as the one that demonstrates the best performance in the previous test (Table 2: Otsu’s method for 5 classes) and the previous processing step, i.e. the approach to select the image from which the ellipse is extracted, changed according to the test. Table 3 shows these results. In the first row the optimal diffusion time was calculated based on the approach presented in this work and the other rows the thermal diffusion time was fixed at 0.05, 0.1, 0.15 and 0.2 seconds. These values were chosen based on the mean optimal diffusion times obtained in the previous experiments when it did not exceed 0.2 seconds.
Table 3: Result of fiber orientation assessment using different diffusion times to select the original infrared image.

<table>
<thead>
<tr>
<th>Diffusion time</th>
<th>Mean ori.</th>
<th>STD</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal(^{(a)})</td>
<td>90.62°</td>
<td>3.99°</td>
<td>0.31°</td>
</tr>
<tr>
<td>0.05 seconds</td>
<td>90.62°</td>
<td>4.96°</td>
<td>0.39°</td>
</tr>
<tr>
<td>0.1 seconds</td>
<td>90.39°</td>
<td>7.10°</td>
<td>0.32°</td>
</tr>
<tr>
<td>0.15 seconds</td>
<td>90.54°</td>
<td>4.07°</td>
<td>0.32°</td>
</tr>
<tr>
<td>0.2 seconds</td>
<td>90.74°</td>
<td>4.14°</td>
<td>0.32°</td>
</tr>
</tbody>
</table>

\(^{(a)}\) based on the largest eccentricity.

Results presented in this section are discussed next.

4. Discussion

The optimal diffusion time selection method proposed in this work showed the best performance in our experiments (see Table 3). When one uses a fixed diffusion time for all inspections, the error of the method increases as can be seen for the cases 0.05, 0.1, 0.15 and 0.2 seconds. Thus, it can be stated that it is better to select the thermal diffusion time for each inspection individually based on the eccentricities of the thermal patterns of the first couple of seconds of the inspection.

Different methods for selecting the optimal threshold for the ellipse segmentation can be used and numerous methods are available in the literature. In this work three methods were selected in order to determine threshold values. The ellipses were segmented using Equation 1 where \( T_h \) is each of threshold values selected by the different methods. The orientations of the ellipses’ major axis were calculated along with some statistical values reported in Table 2. The valley emphasis method was the one which had the worst performance both visually (by analyzing the ellipses segmented with the threshold values calculated by this method) and statistically (by comparing standard deviation and error values reported in Table 2). The other two methods, i.e. Otsu’s and Rosin’s
methods, displayed better results.

Nevertheless, a variation of Otsu’s method was tested. In order to refine even more the segmented ellipses, threshold values to segment the image in more than two classes were also calculated. Due to experimental observations, it was decided that the ellipse from which the fiber orientation would be determined was going to be the one segmented from the second thresholded class (see Figure 6). The ellipses segmented using threshold values for 3, 4 and 6 classes displayed a performance similar to the one achieved with Rosin’s method. The ellipses segmented using the threshold value for 5 classes displayed the best performance. It should be highlighted here that the statistical differences obtained by changing the threshold selection method are not very large but they exist. For instance, using Rosin’s method we obtained a standard deviation of 4.33° and standard error of 0.34° while using Otsu’s method for five classes we obtained a standard deviation of 3.99° and standard error of 0.31° which is clearly an improvement.

5. Conclusions

In this work an active infrared thermography technique using diode-laser for fiber orientation measurement on CFRP was presented. A small spot is heated on the surface of the sample and the diffusion of the heat on the surface provides indication of the fiber orientation. In the case of CFRP laminates which have fibers oriented in one direction, the thermal pattern on the surface will have the shape of an ellipse and its major axis orientation will be the same as the direction of the fibers. The selection of the ellipse from the infrared image sequence is done based on the eccentricity of the pattern of each image in the sequence. The image with the largest eccentricity is chosen and from this image, using a method for automatic optimal thresholding selection, a binary image is segmented and fiber orientation of the binary shape calculated.

In order to assess the performance of the described method, three different laminates with known fiber orientation (±90° on the surface) were inspected. A total of 32 different points on each sample were tested five times each. For
each inspection, the fiber orientation was computed using the proposed method and latter standard deviation and error values were used to compare different approaches. The best approach was obtained using the optimal diffusion time selection based on the largest eccentricity and Otsu’s method for five classes for automatic threshold selection. Results showed that the proposed method can measure the fiber orientation on the surface of a CFRP with an error of 0.31° and a standard deviation of 3.99° which seems to be acceptable values for an application like this since fiber orientation in CFRP laminates are, in most cases, typically cut within ±2° of the nominal targeted fiber orientation angle on each ply. Additionally, even though the other methods for automatic optimal threshold selection were outperformed in our experiments, it does not mean that they are not viable methods. It means that they are not suitable for the application addressed in this work; however there are other applications where they would perform better.

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References


