Measuring Strand Orientation in Carbon Fiber Reinforced Plastics (CFRP) with Polarization

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Abstract. Carbon Fiber Reinforced Plastics (CFRP) are increasingly popular for lightweight but strong components, for example in aircraft or automotive applications. These materials come with the advantage of a large design space of the resulting material properties. A structural component can be tailor made for a specific load while minimizing the total weight of the component. However, this requires a non-uniform material where the strength and stiffness is controlled by defining the placement and orientation of individual fiber strands within the composite. For obtaining the desired properties of a component, a careful manual lay-up of fiber material in the correct orientation needs to be carried out. This poses a high risk that an assembly error could cause a failure where the structural component will not withstand the designed loads.

We have developed a digital camera that can assist in the assembly process by measuring and visualizing the carbon fiber orientation. The used principle is as follows: The carbon fiber strands influence the incident light and mainly reflect light of a certain polarization orientation. With regular unpolarized illumination (as present in typical working environments), the polarization of the reflected light can be measured and directly gives the orientation of the fibers. This is possible for the uppermost layer of fibers, even with resin being applied. The degree of polarization shows areas where fibers are present. Other material like paper reflects unpolarized light which allows for an easy distinction.

The developed camera operates with a single image sensor where adjacent pixels are sensitive to different angles of polarization. This way, the camera captures the orientation of polarized light in a single image. The PC software then processes the raw data and displays intensity, the degree of polarization and the angle of polarization which directly corresponds to fiber orientation. The easy to use system operates live which enables direct user feedback but can also be used for storing photos for documenting the lay-up process.
Introduction

Carbon Fiber Reinforced Plastics (CFRP) are a unique class of materials that is stronger in combination than the individual components. In addition, the stability is controlled by the order and layout of the combination of individual layers. Such a specifically targeted material can thus be lighter, stronger and stiffer than metals. This set of features is especially interesting in high-end but weight restricted applications like automotive or aircrafts [3].

However, the increased flexibility in the design space also comes at an increased cost and complexity. A CFRP is a non-uniform material where the strength and stiffness is controlled by defining the placement and orientation of individual fiber strands within the composite. In addition, the material is often anisotropic, providing different properties along different orientations within the material. For achieving minimum weight, a systematic design and simulation of the components need to be carried out [2] and a careful manual lay-up of fiber material in the correct orientation is required. For example, an angular error of 5% can lead to a 20% reduction in strength [14]. Furthermore, for machining and assembly, the workflow needs to be adjusted to prevent damaging of the composite [1]. Still, an assembly error comes at the risk that a component will not withstand the load and experience a catastrophic failure. Thus, testing of CFRPs plays an important role in manufacturing.

In destructive testing, an analysis of the failure modes leads to improved design principles [4] which can be applied to new designs. However, this does not guarantee that individual pieces are alike and made to specification. An analysis of individual pieces can be achieved with non-destructive testing. For general polymer composite materials, an overview of measurement techniques is shown in [5, 12]: For example ultrasonic, acoustic and heated thermographic principles are available. Furthermore, eddy current measurement [10] and x-ray and computed tomography imaging [11] are commonly used. With these technologies the analysis of the finished component and after failure is carried out. However, they offer no assistance and control during the assembly procedure. In contrast, we present a novel polarization-based imaging technique that is directly able to image the orientation of fiber strands. This way, contact-less quality inspection is directly possible during manufacturing.

The remainder of the paper is organized as follows: The polarization based technology for non-destructive non-contact visualization of CFRP is explained in the following section. Then, measurement examples for our system are shown.

Polarization-based CFRP Analysis

We observed a novel optic property of carbon fibers that they reflect polarized light when illuminated with uniform non-polarized light [8]. We believe that the underlying physical effect is similar to that of the well-known wire grid polarizer [9]. For carbon fibers, this effect is equally present both in the visible range, as well as in the NIR spectrum of light. For illumination, an unpolarized light source is sufficient, which simplifies illumination with area lighting, as reflection-based dome illumination can directly be used. An illustration of the measurement setups is shown in Figure 1.
In analysis of the reflected light, the following polarization components are analyzed:

- The intensity of the reflected light is important as a control. With directional reflections and black material some illumination situations will lead to no intensity being reflected. Without light, no polarization, and thus no angle can be measured at that point of the object.

- The degree of linear polarization (DOLP) shows the ratio of polarized and unpolarized light. While the direct reflection from the fibers gives a high DOLP and thus a good discrimination, reflection at the surface of the polymer and scattering through the polymer contribute unpolarized light.

- The angle of maximum polarization (AOMP) finally corresponds to the angle of orientation of the fibers. The measurement of the angle is only valid with a certain DOLP being present. By definition, if the DOLP is zero, no angle can be measured.

The proposed measurement principle is able to measure the orientation of carbon fibers. The measurement can be carried out from a certain distance, thus, it does not interfere with manual assembly and certainly does not need contact. This is an advantage as there is no danger of contamination of the optics with polymers. The measurement is limited to the uppermost layer, as no light penetrates the fibers. As demonstrated in Figure 5, a small gap in the top layer of fibers is sufficient for seeing and analyzing the fiber orientation of the layer below. The technology is thus best-suited for in-production analysis of raw material and of the lay-up process.

For measurement and analysis of polarized light\(^1\), at least three measurements are required. A linear polarization filter is used in the analysis in different orientations as shown in Figure 2. Many applications capture intensities for 4 filter orientations which can be used for reducing image noise. From the intensities captured by a camera after the filter, one can calculate the Stokes parameters and the intensity, DOLP and AOMP [13]. Although this time-sequential approach is accurate and widely used in scientific applications, it comes at the drawback that multiple images need to be captured. The rotation of the polarization filter requires a certain time – in the meantime the object must not move. This setup is unsuitable for in-line object inspection or live video quality inspection applications.

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\(^1\) For this analysis we are only interested in the linear polarization of light. For now, the effects of circular polarization will be excluded in this discussion.
As an alternative for online and live measurements, we use our polarization camera POLKA. This camera is equipped with a custom-built image sensor [6] where individual pixels are equipped with individual polarization filters [7]. This way, a single captured image from the camera contains all information required for reconstructing the polarization information of the incident light. The principle of division-of-focal-plane imaging is well-known from Bayer pattern RGB sensors and trades in some spatial resolution for speed. Figure 3 shows the sensor layout principle, the integration of the polarization wire grid filters into the pixel and the completed camera. The integration of the wire grid polarizers into the CMOS sensor metal layers has the major advantage that for manufacturing of the sensor, no extra process steps are necessary. The sensor can thus be fabricated without extra cost compared to a regular image sensor.

![Sensor Layout](image)

With the POLKA camera, the measurement of fiber orientations can be carried out in-line and even for moving objects. The camera is robust and industry-proven and comes with standard USB3 and GigE interfaces, which allows for an easy integration into testing machines. The currently available version (Polka02) delivers 640x480 pixels at 100fps. A system with higher spatial resolution is being worked on.

![Camera System](image)
Measurement results and examples

In this section we show some results of CFRP measurements. We used two different camera systems for generating the images: Examples from our current POLKA polarization camera illustrate the image quality and resolution that can be achieved in a live single-shot imaging scenario. For comparison, a reference polarization camera based on a rotating filter is used. This setup can only capture images of non-moving objects, requires some further offline post processing, but delivers a higher spatial resolution.

The example in Figure 4 shows a real-world CFRP component from an aircraft. In this example, the contrast is low due to a dark polymer. In the left image one can see the grayscale intensity image which shows hardly any contrast – for analysis of a defect this would not be useable. The false-color polarization image on the right encodes the AOMP with color. One can clearly see the fiber orientation in the red dots and a fault-line going through the image.

The next example in Figure 5 depicts a carbon fiber tube, held by only little clear polymer. Thus, the fibers are perfectly visible on the outside. The first images depict the 4 orientations captured by the reference camera. For the human observer, they look quite similar. After processing, the DOLP image is generated where an intensity >0 shows that the reflected light is highly polarized. For reference, the Intensity image depicts the situation that a regular camera would see. Hardly any features can be discerned and the fiber orientation is hard to notice. This shows that the inspection with a regular camera is challenging. Finally, the bottom image shows the HSV false-color representation containing the polarization information: The angle is depicted as color, the saturation shows the DOLP and the intensity is shown as intensity. A high degree of polarization is visible from the colorful image. The orientation of underlying fibers is visible in small gaps, showing that a measurement in small regions is possible.
Figure 5: Polarization image of a CFRP tube. The top grayscale images show the raw data for different filter angles, the calculated DOLP and Intensity. The bottom image shows the false color representation where the fiber orientations are clearly visible.
Figure 6 shows the results for a CFRP with a regular mesh under a clear polymer. This sample is without major defects and will be used to further classify spatial image resolution and angular accuracy of the proposed measurement principle.

Conclusion

The unique mechanical properties of carbon fiber reinforced polymers (CFRP) highly depend on a good design and correct lay-up of individual fibers. Even small angular errors can lead to significantly reduced strength. We present a novel principle for in-line quality inspection based on polarization imaging. We found that uniform unpolarized light if reflected as polarized light in the orientation of the fibers. With our POLKA polarization camera this orientation can directly be measured and displayed. Exemplary images demonstrate that contactless fiber analysis is directly possible with the proposed setup.

References


