Development of a method for the non-destructive evaluation of fiber orientation in multilayer 3D carbon fiber preforms and CFRP with robot-guided high-frequency eddy current testing technology

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Abstract. This paper presents results of recent cooperative works at the ITM and IKTS on the 3D fiber orientation measurement with eddy current technique, which are the result of a recent dissertation. For the development of CFRP with load-adapted fiber orientations, a process is required that is able to nondestructively measure the fiber orientations in multi-layer, 3D preforms and CFRP structures.

Eddy-current testing (ECT) with frequencies in the megahertz range is able to reveal the filament structure in multilayer CF structures. To further expand its applicability a method is developed that can automatically generate the robotic paths for robot-guided ECT from an arbitrary 3D surface. From the obtained EC images, the local fiber orientation is determined on a grid of evaluation points. For this purpose the surface in near each point is projected onto a plane and converted into a pixel image. Fourier transformation is used to calculate the main fiber directions which are assigned to the individual layers by means of a robust algorithm and strategies are developed to exclude false information caused by faulty measurements or the misinterpretation of edges from the fiber orientation measurement.

The method is tested on a 3D geometry, a complex four-layer CFRP component. The fiber orientations can be determined in all four investigated layers. The results can be used to improve forming strategies and draping simulations or as inputs to structural simulations of CFRP components to verify the structural integrity under expected loads. This allows to further optimize CFRP design and manufacturing processes, exploiting CFRP's full potential in order to minimize costs and resource consumption while maximizing durability and robustness in aerospace applications.
1. Introduction

This paper presents results of recent cooperative works at the ITM and IKTS on the 3D fiber orientation measurement with eddy current technique, which are the result of a recent dissertation [1]. Preliminary results, which are not included here, have also been published in a number of articles [2, 3]. The outstanding mechanical properties of carbon fiber reinforced plastics (CFRP) are achieved by adjusting the orientation of the load-bearing carbon fibers exactly to the type and direction of the external loads acting on the structure. If the property potential of the fibers is fully exploited in this way, CFRP can be used to realize load-bearing structures that are up to 70% lighter than steel and up to 30% lighter than aluminum with the same load-bearing capacity [4]. Additionally to the weight saving, composite structures offer the further benefit of being able to integrate smart measurement systems [6] or functional components [7].

On the other hand, any deviation of the yarn orientation from the load direction must be compensated by additional material. A deviation of the fiber orientation reduces the stiffness by up to 5%, the strength by up to 20%. Each fibre angle deviation thus increases the weight, increases the material and manufacturing costs and in many cases makes production with traditional light metals more economical [5].

The prerequisite for exploiting the property potential of CFRP to reduce weight is precise knowledge of the fiber orientation in the component. Without this knowledge, manufacturing processes cannot be systematically optimized, draping simulations cannot be validated and component design cannot be carried out reliably. Significant research resources are currently dedicated to mapping the entire CFRP development process in a virtual process chain and designing the semi-finished products and manufacturing processes on the basis of the desired fiber orientations in the component. Without a process that confirms the validity of the statements made about the fiber orientations after the manufacturing process, enormous uncertainties must always be accepted in these virtual process chains. It is not sufficient to analyze only the fiber orientation of the top layer or the deformation behavior of each individual layer, because the fiber orientation is essentially dependent on how many layers are formed together and in which order they are stacked.

There is currently no method that can non-destructively measure the yarn orientation in multilayer, three-dimensionally formed CFRP components. Optical methods are highly precise when measuring the fiber orientation, but can only examine the fiber orientation in the uppermost layer and provide neither the information required for component design nor for process optimization [8 – 12]. Micro X-ray CT investigations, on the other hand, are able to measure the fiber orientation in the inner layers of a CFRP component, but are complex, cost-intensive and limited to small samples [13 – 17]. High-frequency eddy current testing is a method that permits the measurement of fiber orientation in multilayer carbon fiber structures [18 – 22]. In contrast to traditional eddy current testing, measurement frequencies in the megahertz range are used to make the course of the weakly conductive carbon fibers in the component visible with the aid of eddy currents. As shown in Fig. 1, not only the fiber orientations of the top layer are visible, but also those of deeper layers.
While the measurement of the fiber orientation in two-dimensional textile semi-finished products and semi-finished product stacks using the eddy current method is state-of-the-art, there is currently no method for full-surface measurement of the fiber orientation in multi-curved components as required for process development and quality assurance in CFRP production [23 – 26]. The aim of this contribution is therefore to develop a method based on high-frequency eddy current testing technology for measuring fiber orientation in three-dimensional, multi-layer carbon fiber preforms and CFRP. Since eddy current testing is based solely on the conductivity of the carbon fibers, such a method, in contrast to ultrasonic testing, can be used both for dry preforms - three-dimensionally formed and fixed stacks of semi-finished products that are passed on to the infusion process - and for the cured composite components themselves.

Eddy current testing of carbon fiber materials uses imaging eddy current testing and rotational eddy current testing as measuring principles. In eddy current imaging, the sensor is moved over the component surface in several paths. From the measured impedance at the individual measuring points an intensity image of the surface (eddy current image) is generated, comparable to a C-scan from ultrasonic testing. Since the conductivity of each fiber bundle is higher at the center, the highest eddy current densities are generated when the transmitting coil is located centrally above a fiber bundle of this layer. When scanning the surface, a superimposed striped pattern is created, which indicates the thread orientation of the individual layers. In addition to the fiber orientation, local defects can also be detected in the eddy current image due to the different conductivity, which is not possible when using rotational eddy current testing. Commercial 2D inspection systems for eddy current imaging of carbon fiber materials are distributed by Suragus GmbH, Germany and Fraunhofer IKTS.

The determination of the fiber orientation from 2D eddy current images was carried out in all previous work by evaluating the Fourier transformation, which converts the image to the frequency domain [23, 27 – 31]. Fig. 2 shows an evaluation software based on the Fourier transformation from Suragus for fiber orientation measurement on 2D eddy current images. In addition to the fiber directions, the software allows the automatic detection and quantification of paths, undulations and local defects.
Various test systems were developed for testing single curved, so-called 2.5-dimensional test specimens. Salski [33] introduces an array scanner that is equipped with a flexible sensor arm and can therefore detect simply curved surfaces (Fig. 3 left). Printed planar coils are used as sensors. Since the individual coils have a different angle of tilt to the surface with double curved surfaces, the measuring signals are subsequently adjusted by averaging. A 2.5D scanner (Fig. 3 right) distributed by Suragus in cooperation with Fraunhofer IKTS has a tilting mechanism of the z-axis, so that slightly curved components can also be inspected. Both systems extend the testability for 2.5-dimensional test specimens, but do not allow testing of multiple curved surfaces. Since no shear occurs during the draping of textile semi-finished products to 2.5-dimensional test specimens, thus maintaining the original thread orientation, these are not relevant for fiber orientation measurement.

In addition to these 2.5-dimensional systems, Fraunhofer IKTS has developed a system that enables eddy current testing of multiple curved surfaces. For this purpose, an eddy current sensor was integrated into an industrial robot. With the aid of a strip light projection, the surface and the position of the test specimen are recorded, followed by path planning with the aid of dedicated software, in which parallel test paths are projected onto the surface. After a collision check in a robot simulation, the test procedure can be carried out. An evaluation software is available for visualizing the results.

For the first time, an inspection system is available that is able to detect even multiple curved 3D surfaces and to visualize the yarn gradients in three-dimensionally formed carbon fiber materials. The advantages are a fully integrated, easy-to-use path planning and inspection software. However, a major limitation of this work is seen in the fact that the path planning is carried out by a point projection. This method requires little computing effort and can be controlled very intuitively, but in the case of complex components with inclined or vertical side surfaces it results in fewer or no paths being placed on the side surfaces, so that the measurement must be carried out in several sub-steps. Furthermore, although the three-dimensional yarn gradients are made visible, it is not possible to measure
the yarn directions on the 3D data. Consequently a method is developed to calculate robotic paths with a defined maximum distance on any three-dimensional surface. In addition a method to robustly measure fiber orientations in multiple layers in three-dimensional preforms and CFRP components.

2. Materials and Methods

2.1 Robotic Path Planning

As an input to the path planning software CAD data of the object to be investigated is used. The representation of the 3D surface is an approximated triangulation mesh, which is derived from the given CAD data. This allows the representation of non-unique (i.e., not as a function $z = f(x,y)$ representable) surfaces with vertical edges and undercuts, on the one hand, and a fast calculation of basic geometric operations (intersection line/surface, normal vector, progress by defined arc length on the surface), on the other hand. By specifying a sufficiently small triangle size, even strongly curved 3D surfaces can be modelled with sufficient accuracy.

There are two strategies for calculating the paths on the 3D surface: firstly, the starting points of the individual paths can be located with the specified path distance. The paths are then calculated so that they follow a given direction on the surface (method 1, Fig. 4 left). On the curved 3D surface, however, the paths have, depending on the surface curvature, a distance different from the specified path distance, resulting in additional paths being inserted to such an extent that the specified path distance is not exceeded. The calculation of additional paths between the calculated paths can be avoided by a second strategy, in which the first path is given on the surface, and the points of the following path are calculated in such a way that they have a constant distance to the points of the first path (method 2, Fig. 4 right). A curved surface still requires additional paths. In contrast to method 1, however, the filling paths are placed at the end of the calculated paths.

Fig. 4. Strategies for path planning: Starting points and path vector (left) or starting points and first path (right)

Both methods are mathematically similarly complex, but the first method has the advantage that the start and end points of all paths lie on one line and all paths run similarly, which simplifies the collision and accessibility check. Therefore, a method for surface detection based on method 1 is developed.

1. The starting point for the calculation of each path is the starting point and the same path vector for all paths. For a uniform interpolation point distance, equal distances on the surface in the direction of the path vector must be determined, which is done by the following algorithm (see Fig. 5).
2. Find the corresponding triangle for the starting point. Project the path vector into this triangle and add it to the first starting point. Determine the intersection of the direction vector with the triangle edge to which the direction vector points.

3. Find the next triangle that contains this intersection edge. Project the path vector into this triangle and add it to the calculated intersection. Find the intersection with the next triangle edge.

4. Check if the traveled path has exceeded the specified path distance. If yes, the next interpolation point on the way section lies in the current triangle and is calculated by dividing the distance.

Repeat steps 1 to 4 until the limit of the defined measuring range or surface or the specified number of paths is reached. The limit of the surface is reached if no second triangle containing the same triangle edge is found in step 2. The current triangle then lies at the edge of the surface.

If the specified maximum path distance is exceeded for at least one of the support points, a number of fill lines are inserted between the two paths so that the maximum path distance is guaranteed for all support points.

Fig. 5. Path calculation on triangulated surface and result for a complex 3D-geometry

The sensor orientation for each point is calculated from the normal vectors of the surface and converted to the euler angles (positive rotation around Z-, Y- and X-axis) used in the resulting robotic program. Since small radii (< 15 mm) cannot be scanned without a lift-off of either transmitter or receiver coil, it is acceptable to restrain the euler angles at these points in order to avoid collisions and improve inspection speed.

2.2 Eddy current measuring and evaluation system

For eddy current testing an EddyCus Integration Kit (developed by Fraunhofer IKTS) is employed. To avoid lift-off effects due to a large sensor geometry a special 3D-printed probe with a small coil diameter of 3.3 mm is used. It is attached to an adapter plate via a spring-loaded linear guidance, which is mounted on an industrial robot Kuka KR6 R900 sixx, Agilus (Kuka AG, Germany) (Fig. 6).
The system uses a time-trigger approach. After receiving a trigger input, the measurement data is recorded at a constant measuring rate until the trigger signal is set to OFF. At the end of each path (trigger signal = OFF), the control software stores all recorded measured values together with a time stamp. To determine the x,y,z coordinates of the measured values of the individual paths, the eddy current software expects a file for each measuring path, which contains the actual movement of the robot (time stamp + x,y,z coordinates). The coordinates for the individual measured values can subsequently be determined by temporal interpolation.

The result of the 3D eddy current test is a measurement data set in which each x,y,z measuring point is assigned a complex impedance value (real and imaginary part). If all real and imaginary values of a measurement are displayed in the complex plane, the result is a point cloud in the complex plane. The eddy current signal is affected by several effects, especially differences in conductivity, lift-off and thickness. A separation of the different effects is possible if they have different directions of action in the complex impedance or voltage level. Consequently, the point cloud must be rotated in such a way that the interference effects are minimized when projecting the rotated point cloud on the x-axis. The optimal phase rotation, which maximizes the contrast of the carbon filaments, can be determined by a principal component analysis.

2.3 Measuring the fiber orientation

For the measurement of the local fiber orientation at an evaluation point, the stripe pattern of the carbon fibers in the vicinity of this point must be observed. All known image analysis methods (see e.g. [35]) require a 2D image with a constant x and y point grid (pixel grid(bitmap), so that the 3D surface in the vicinity of the point must be smoothed, i.e. projected into a plane.

For this projection, the normal vector of the tangential plane to the surface, $X_n$, is determined at the respective evaluation point $X_0$ (for the definition of the evaluation points see below). Then all points $X$ of the environment are projected into this tangential plane:

$$X_{proj} = X - ((X - X_0) \cdot X_n)X_n$$  \hspace{1cm} (1)

However, this procedure must be extended by a correction: in the vicinity of strong curvatures, the projection would lead to distortions, which is corrected by extending the distance $X_0X_{proj}$ so that it corresponds to the original distance of the point $X$ to the evaluation point, $X_0X$. To further enhance the image quality a high-pass filter is applied that accentuates the carbon fiber bundles. Subsequently, noise is reduced by applying a Gaussian filter.

As a next step the 2D-FFT is used to measure the fiber orientations which are then mapped onto the 3D-surface. If there is not enough image information to determine all fiber orientations in an evaluation section, e.g. if it is located on the edge of the scanned surface, the information will be calculated by interpolating between adjacent evaluation points.
3. Results

Fig. 7 shows the obtained 3D eddy current image for a complex CFRP component and sensor orientation 0°. The component has a layer structure of \([+45^\circ/-45^\circ/0^\circ/90^\circ]\) and both the upper \(+/-45^\circ\) layers and the lower \(0^\circ/90^\circ\) layers are clearly visible as a stripe pattern in the eddy current image.

Lift-off effects are unavoidable at the longitudinal and transverse ribs as well as at the edges (bright areas): due to the narrow geometry radius, either the receiver coil or the transmitter coil of the sensor loses contact with the surface. The phase rotation can reduce these interferences, but not completely eliminate them, so that the ribs are excluded from the fiber orientation measurement in order to avoid false detections. This is not necessary for the edges, since the fiber orientation measurement algorithm automatically detects edges in the image section and prevents a false detection of an edge as the fiber direction.

Fig. 8 shows the reconstructed fiber orientations for all four layers according to the presented method. The results are validated qualitatively by comparing the course of single rovings in the eddy current image to the detected fiber courses. As can be seen in Fig. 8 the measured fiber courses in the plane as well as in the curved areas correspond very well with the stripe patterns recognizable in the eddy current image.

For an optical validation of the measured fiber orientations in the upper layer, the component was photographed in vertical perspective and the 2D photo was mapped onto the 3D surface of the measurement data (Figure 9). The fiber orientations determined with the eddy current inspection follow the optically recognizable fiber orientations very well.
Nevertheless only the top layer can be validated quantitatively due to the lack of alternative methods to measure fiber orientations of deeper layers.

4. Conclusion

The development of carbon fiber-reinforced plastics with load-bearing fiber courses requires a process capable of non-destructively measuring the fiber orientations in multilayer, three-dimensionally formed preforms and CFRP structures. Previous work has shown that imaging eddy current testing with frequencies in the megahertz range is capable of imaging the yarn structure in multi-layer two- and three-dimensional carbon fiber structures. In this article a method is presented that can fully capture any 3D surface, even in the presence of strongly curved and vertical areas with uniform path spacing, and thus ensure a defined distance between the measuring points. This procedure serves as a basis for the development of robot programs for eddy current inspection of three-dimensional surfaces. From the measured eddy current images, the local fiber orientation is determined on a grid of evaluation points. In a first step, the surface in the vicinity of each evaluation point is smoothed and converted into a pixel image, which is pre-processed to increase the yarn contrast. The Fourier transformation is used to calculate the local fiber orientation distribution, from which the main fiber directions are calculated and assigned to the individual fiber layers using a robust method. The developed method was tested on a complex CFRP component and validated optically.

The developed process is the first to provide a tool that allows the non-destructive measurement of fiber orientation in multilayer, three-dimensional carbon fiber preforms and CFRP and can be used for the systematic optimization of 3D preforming processes. The resulting CFRP structures will have fiber orientations precisely adapted to the external loads, which exploit the lightweight construction potential provided by the CFRP material.
References


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