Measurement of Rotor Blade Deformations of Wind Energy Converters with Laser Scanners

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Abstract. Wind energy converters in operation are exposed to high stresses which result in large deformations of the rotor blades. In this paper a method for determination of deformations of rotating rotor blades is presented using multiple synchronous laser scanners and cameras. In a first step, multiple scanners in 1D mode are used which record cross sections at different positions along the rotor blades. By comparing the recorded cross sections with a CAD model of the rotor blade, the deformations in out-of-plane and torsional direction can be derived. In order to ensure that the positions of the cross sections are defined in the coordinate system of the wind energy converter, the nacelle is pre-scanned and a 3D transformation is performed using known coordinates from the manufacturer. To account for the relatively slow movement of the nacelle, it is observed by a photogrammetric camera. The results of the nacelle´s motion are considered in the analysis of the 1D data. First test recordings were carried out with different measurement frequencies to enable comparisons of accuracy. Furthermore, first results of the cross-section measurements are presented. For the next step the 3D scans will be evaluated which have been acquired using a further instrument simultaneously with the 1D scans. In the same way as before the 3D points will be transferred to the reference system of the nacelle, and then combined with the 1D data.

1. Introduction

The objective of the project WindScan, managed by the Jade University of Oldenburg, is the detection of deformations of a moving rotor blade in 1:1 scale with several synchronously operated laser scanners. A wind energy converter (WEC) is observed during operation whereby the rotor blades are of particular interest. The rotor blades are a key component for the performance of the WEC. Blades are constantly being optimized to save costs and improve efficiency [1].

Until now the blades are tested in large laboratories for certification by static or cyclic testing. In this case the blade is, for example, set in forced oscillation for a long time and observed by photogrammetric means [2-4]. Bending tests also offer the possibility to measure the shapes of the blade and its changes.

For better monitoring of the system during operation different techniques are already installed [5]. Strain gauges can be attached to the rotor blades. They are susceptible to systematic errors; especially the temperature affects the results [6]. Therefore, the actual deformation of the blades cannot sufficiently be described.

Schmidt Paulsen et al. [7] attached reflective targets to rotor blades and tower, and observed them with two stereo camera systems. Another recent project concerning the capture of the aero-elastic deformation takes place at the Institute ForWind, a joint research center of the universities of

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Oldenburg, Hannover and Bremen [8]. Here, the blades are covered with a random pattern and observed with a stereo camera system. By image matching procedures local deformations shall be derived.
As a major drawback of both approaches the WEC has to be stopped for an extended period of time in order to glue the blades with a texture film and to remove them again later. The aim of the project WindScan is to measure several degrees of freedom using laser scanners and cameras without targeting the object.

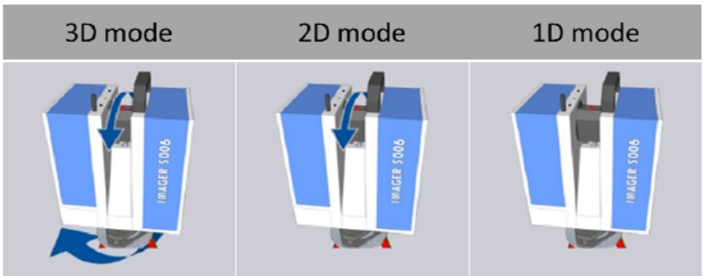

Figure 1. Operating modes of the laser scanner [11]

2. Basics and State of Art

2.1 Laser scanning

Laser scanning is a contactless 3D measurement method. It enables the measurement of distances and corresponding angles with a frequency of up to 1 MHz. Most common applications of laser scanning are concerned with capturing of static objects. Different operating modes are possible, their principles are shown in Figure 1. The sequential acquisition of individual points results from the rotation of the laser around the horizontal and vertical axis (3D). Alternatively, typical mobile mapping systems use the rotation of only one axis (2D) while the movement of the mobile platform of the scanner provides the third dimension. For allocation/referencing into a global coordinate system other sensors such as GPS, INS or cameras are necessary [9, 10].
On the other hand, a moving object can be observed from a fixed position and with a fixed orientation (1D). For the allocation of the measured points the orientation and position of each measurement has to be acquired with additional sensors. In [12] an investigation is presented dealing with the recording of a moving ship. The movements were registered by three target-tracking total stations for the geometrically correct registration of the point cloud. The ship itself was assumed to be stable. The synchronization of the total station and the scanner was done by synchronized watches.

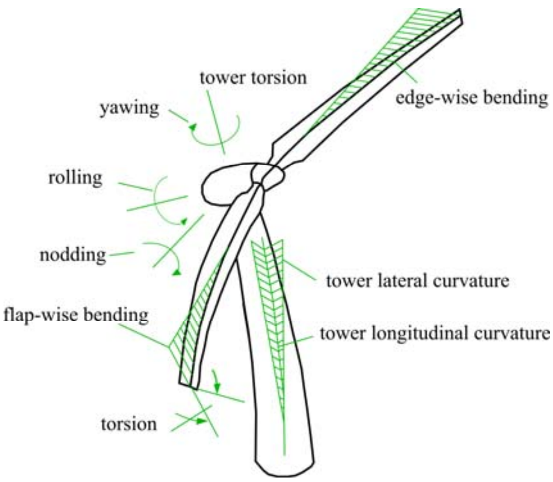

Figure 2. Degrees of freedom of the WEC (adapted from [2])

2.2 Wind Energy Converter
The measurement object is a 6M126 turbine of Senvion SE [13], designed for offshore use and installed on land in northern Germany. It has a hub height of 100m, a blade length of 61.5m, and the nacelle measures approximately 17m x 7m x 6m.
WEC are subject to particular stresses which can be critical due to their continuous change, especially caused by wind pressure, centrifugal forces and gravity. The top speed on the outer tip of the blade can reach up to 80m/s. These forces lead to bending of the blades of up to 10% of the blade length [14].
The tower bending must not be neglected and varies over time. Until now the effect can sufficiently be described as a shift of the nacelle in the horizontal plane. More degrees of freedom are shown in Figure 2.
To compare the received profile data of the laser scanner with the CAD model of the rotor blade, the profiles have to be transformed into the coordinate system of the hub [15]. Some coordinates of distinctive points or a CAD model with the origin at the hub must be available.

3. The WindScan Project
The aim of the project WindScan is the measurement of several geometric parameters without targeting the object. The basic concept includes a combination of laser scanners and cameras which shall observe the WEC from the ground.

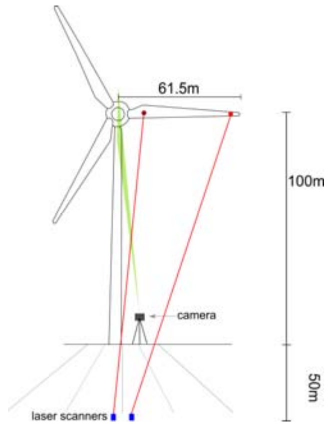

Figure 3. Measuring arrange-ments on WEC

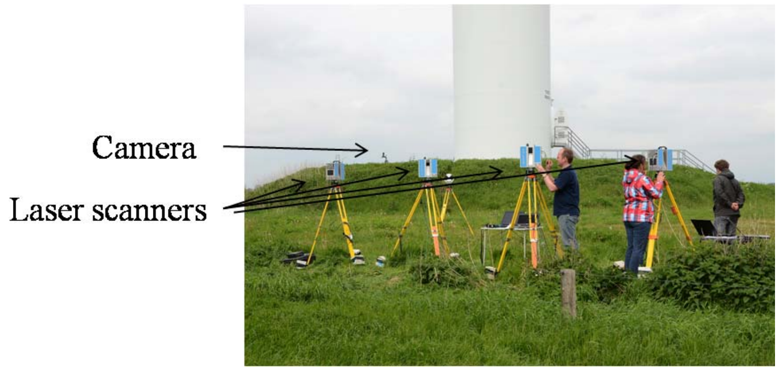

Figure 4. Camera and four laser scanners in the field

3.1. Measurement system
For the determination of deformations, multiple Z+F Imager 5010 [16] are operated in 1D mode, i.e. vertical and horizontal angles are fixed. With rotating blades and a fixed laser beam, the distances form a cross section of one side of the blade describing a profile as a function of time. Paffenholz et al. [17] and Gikas and Daskalakis [18] have also recorded such cross sections with a laser scanner, which, however, were not further analyzed in their pilot projects.
The scanner is able to record data at a sampling frequency of up to 1 MHz. However, with a lower sampling rate, the distances can be detected more accurately, since the device has a longer integration time for disposal of a single measurement [19]. Investigations of the measurement frequency are published in [20]. On the outer tip of a blade the cycle time equals to 0.01 seconds. A sampling frequency of 31 kHz still provides 300 points along a profile, hence it was used in the current measurements.
In Figure 3 the measurement arrangement is shown. The deformations are derived from the cross sections taken at different positions on the blade. By fitting the cross sections into a CAD model of the

blade, the deformations can be calculated. Figure 4 shows a picture of the measurement arrangement. In this field test, four scanners were used. Three scanners recorded profiles in 1D mode. The fourth scanner recorded data in 3D mode for future evaluations. For high accurate scanner synchronization μ-blox GPS modules are used.

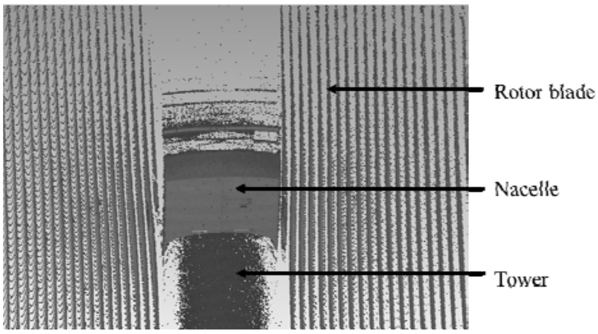

Figure 5. Point cloud of 3D scans of the nacelle. Stripes are hits on the rotating blades.

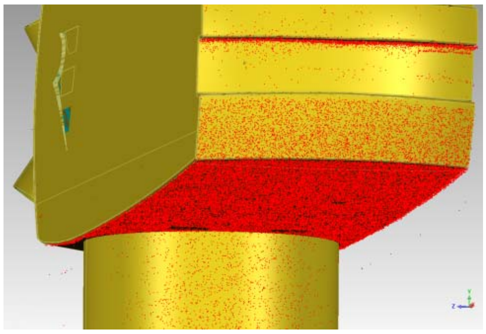

Figure 6. Point cloud of 3D scans combined with a CAD model, calculated with Geomagic Qualify

The scan data are initially given in the coordinate system of the instrument. It is common practice to transform the data into a local stationary system [21], equally for all scanner positions. In the current work, the motion of the object is a critical issue. To make the results useful, a transformation into the coordinate system of the object is essential. A part of the nacelle with known point coordinates is scanned in 3D mode (Figure 5). For the determination of transformation parameters, the point cloud may be adjusted by using a best-fit calculation on the CAD model (Figure 6).

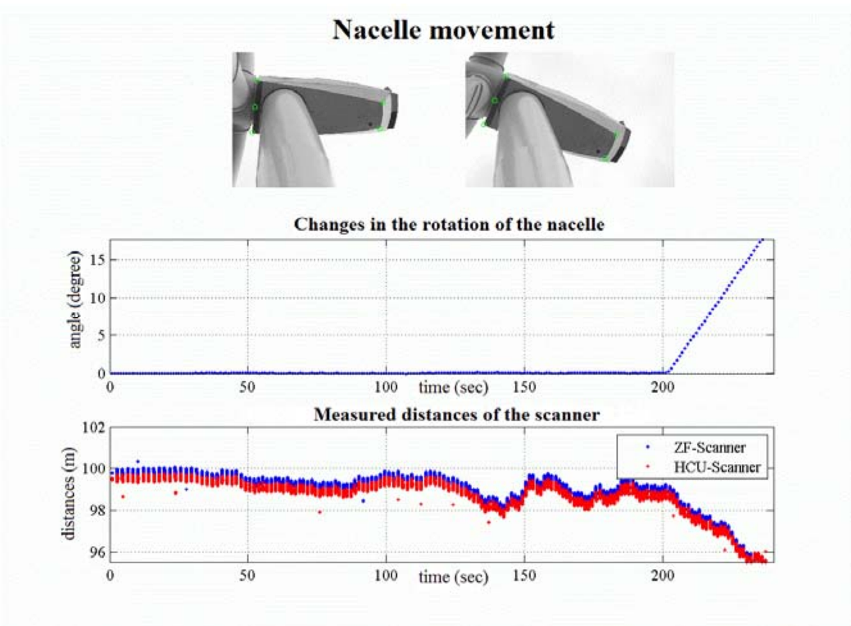

Figure 7. Effect of nacelle rotation on the measured distances; top: camera images of second 0 and 240; middle: change of nacelle rotation over time; bottom: measured distances of two scanners over time

In order to separate deflections of the rotor blade from rotations of the nacelle, which both affect the measured distance (Figure 7), the nacelle is observed continuously with a vertically oriented camera.

A hub height of 100m and a length of the nacelle of 17m lead to a focal length of about 130mm for the complete exploitation of the image format (Nikon D2X). Again a GSP module is used to synchronize the camera with the scanned data.

To calculate the displacement and rotation of the nacelle, the images are analyzed with the institute's program PISA (Photogrammetric Image Sequence Analysis [22]). In this step a point tracking of prominent points is done by least-squares matching. Image coordinates are transformed into the CAD system to calculate the displacement. The scale of the image is derived from known dimensions of the nacelle.

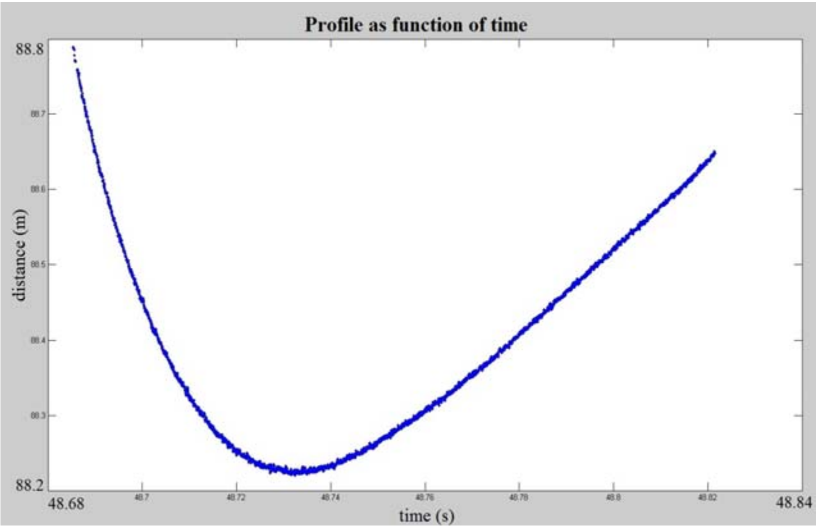

Figure 8. Profile as function of time

3.2. Calculation procedure

In a first step the position of each scanner is calculated relating to the hub coordinate system, utilizing the known coordinates of the nacelle and the 3D scans. With the measured values of at least two points simple triangle calculations can be carried out. An alternative is to use the transformation parameters of a best-fit adjustment of the point cloud and the CAD model (Figure 6).

As a result the positions of the scanner with respect to the hub at the time of the 3D reference measurement are given. The photogrammetric recordings are important for the calculation of new positions because the nacelle may move between the 3D and the 1D scan.

Figure 8 shows the recorded profile of a scanner. With a fixed angle only the distances were recorded and are plotted relating to the GPS time. Because of the fixed orientation it is possible to calculate the rotational speed of the blades. The time between two passes is used. This allows converting the function of time into a function of position (Figure 9).

As starting point, the first measured point on each rotor blade is used. The following points are derived using the time interval and the measurement rate of the scanner.

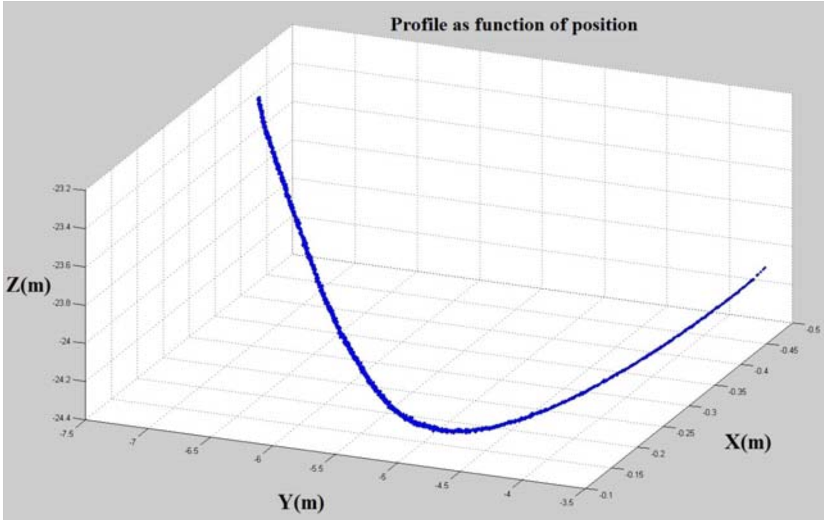

Figure 9. Profile as function of position in the coordinate system of the hub

4. Result

The results are profiles in the coordinate system of the hub. Figure 10 displays a front view of the results of a data set. The tower and the nacelle are shown, and three measured profiles at the original measurement position (the red lines show to the scanner positions). Unfortunately, due to the complex scanner alignment which is not supported in 1D mode, the vertical angles of the scanners were set too low to provide measurements in a horizontal blade position. This process will be further improved in the near future. However, the absolute position of profile points is calculated with an accuracy of about 2-5 cm.

To determine the deformations, the measured profiles are transformed from the original measurement position into the CAD model. From the difference of position and orientation of the profiles, the out-of-plane deflection and the torsion can be calculated (at the given instant). Figure 11 shows an example of the difference between the CAD model and simulated data.

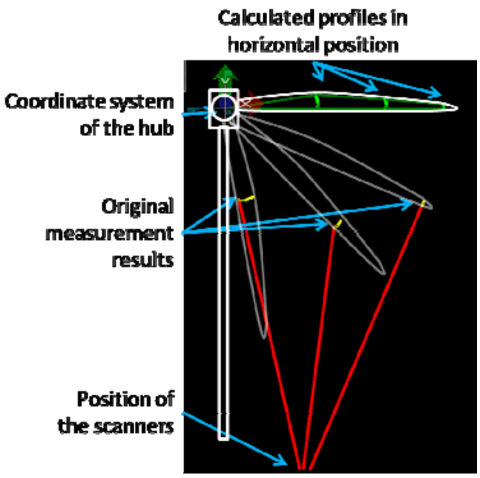

Figure 10. Profiles in the coordinate system of the hub

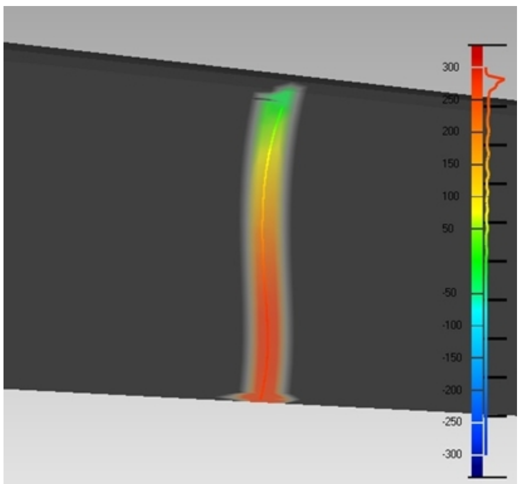

Figure 11. Differences between a point cloud from the simulation calculation and the CAD model [mm]

5. Conclusion

In the present work, a wind energy converter is analyzed during operation with multiple synchronous laser scanners. In order to quantify the deformations of the blades, cross sections are taken in 1D mode of the scanners. For orientation of the scanners into the hub coordinate system, 3D scans of the nacelle are carried out. The movement of the nacelle is observed by photogrammetric techniques.
First results show that deformations of the rotor blades can be detected and evaluated by combination of laser scanners and camera.

Figure 12. A part of a point cloud of a 3D scan, a few profiles are highlighted in red

6. Outlook

Further steps are developments and investigations in the field of combination of the 2D and 3D mode of the scanner. This enables us to measure at different positions almost simultaneously. In 2D mode of such a system, 100 revolutions per second can already be realized.
It is necessary to verify the results of simulations and investigations in a laboratory. Calculation of profiles using the 3D scans could be another method which is currently under investigation. Figure 12 shows a point cloud of a 3D-scan, the profiles are visible (some are highlighted in red). These scans contain all information concerning the shape of the blade and its changes, including the vibration frequency. In the aforementioned measurements a scanner has been operated in 3D mode at the same time the 1D measurement was carried out. Thus these 1D data can serve as a reference for the calculations using the 3D data.
The manufacturers of laser scanners are developing devices with higher frequencies, increasing the unambiguity interval and improving the precision. Therefore it is important to check how suitable they are for the measurement of moving objects and their deformations.

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