AIRTuB: towards automated inspection of leading edge erosion of wind turbine blades by shape analysis

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ABSTRACT

The harsh environment, especially for offshore wind turbines, significantly degrades wind turbine aerodynamic performance and structural integrity. One of the major factors that lowers energy production due to aerodynamic losses is the erosion of the leading edges. Nowadays this erosion is monitored visually, either directly or with drone-based camera systems. In this paper, we address the quantitative characterization of the current erosion state. This enables long-term degradation monitoring to provide crucial information for wind farm maintenance and possible recoating of wind turbine blades. In this project, a customized long-range laser line scanner is used to measure the profiles of the blades at distances of up to 2 m. This distance was identified as a safe clearance between the drone and the blade. Current results include detection of eroded and damaged areas with a sub-millimetre resolution in the laboratory conditions on a real out-of-service blade with the sensor positioned with a scanning frame. Further in the project, a custom-developed heavy drone will be used to scan the blades offshore. The erosion and defect detection approach is based on deterministic analysis of the individual profiles obtained with the laser scanner and includes local analysis of the surface variation, thresholding and clustering of the defects. Later the developed deterministic approach will be benchmarked with machine learning capabilities. Future steps include the integration of the laser line sensor in the drone, hangar flight tests and a series of offshore inspections. This development is done within the smart maintenance innovation project AIRTuB: Automatic Inspection and Repair of Turbine Blades where the inspection expertise is combined with drone developers, wind-turbine manufacturers, repair and maintenance services.

Keywords: leading edge erosion, laser line scanner, defect detection, erosion detection, erosion measurement, drone-based metrology, point cloud, defect feature

1   INTRODUCTION

The harsh environment, especially for offshore wind turbines, significantly degrades wind turbine aerodynamic performance and structural integrity. One of the major factors that lower the energy production due to aerodynamic losses is the erosion of the leading edges [1] which is mainly caused by the precipitation [2, 3]. It was shown in [4] that relatively small eroded surface features, like pits of about 0.3 mm deep and 2 mm wide if grouped (e.g. about 400 pits over a 2.5 m span) can decrease the aerodynamic performance and the power generation by around 3%. This motivates the operating companies to be reliably monitor the leading edge erosion state.

A variety of non-destructive inspection techniques exist to inspect the wind turbine blades [5]. However, most of these techniques provide internal damage detection (e.g. delaminations) and not the erosion of the leading edge which is categorized as external surface damage [4, 6]. Nowadays the leading edge erosion is mostly monitored visually, either directly or with drone-based camera systems. However, only significant defects and damage cases (considerably larger than the indicated pits) can be reliably detected based on the visual [7] and hyperspectral imaging [8], even if supported by the recent advancements in artificial intelligence [9, 10].

Leading edge erosion as an external surface damage can be directly identified if the current blade shape is reliably measured and compared with either the initial measured shape, results from a previous inspection, an analytical shape or a smooth fitted surface. Similar tasks of the blade shape measurement are efficiently implemented during blades production with laser line scanners [11-13] and stereo digital image correlation [14]. Further, optical inspection techniques including fringe

projection and stereovision can be grouped on mobile driving platforms [15, 16] to enable the full-scale scanning of the blades. All these techniques provide a sub-millimetre resolution which is sufficient for the production quality inspection and potentially to identify the small erosion pits. However, the overall weight, dimensions and power consumption of these solutions do not allow them to be used them in the field, especially for offshore inspection which is primarily based on drones.

Up to now, two solutions for quantitative shape reconstruction with drones or with instruments that are highly adapted for that have been published. The first one uses drone-based photogrammetry [17, 18] which achieves a standard deviation for the shape reconstruction of about 1.3 mm with working distance 0.8 m. However, the measuring results strongly depend on the illumination conditions and camera settings. Also, achieving a sensor-blade working distance of 0.8 m in operational conditions is challenging. The second solution uses the structure-from-motion approach where the shape of the leading edge is reconstructed from multiple view observations [19]. Features in the millimetre range were identified within a relatively small field of view at the clearance distance of 2 m.

In this project, a customized long-range laser line scanner is used to measure the profiles of the blades to quantitative characterize the erosion and other damage cases (Figure 1 (a-d)). This sensor choice was made based on a detailed comparison of the optical shape measurement techniques and their applicability to drone-based inspection [6]. The laser line scanner is a rational compromise when the drone-related issues are taken into account (e.g. vibrations, mass and power budgets) together with the real outdoor and offshore conditions (e.g. sunlight, salt-forming on blades). During measurements (Figure 1 (e)), a drone will carry the laser line scanner over the leading edge of the blade. The blade will be oriented with the leading edge up to arrange a reasonable clearance distance of 1.5-2 m which was identified as a safe clearance between the drone and the blade. This distance range is predicted to be safe for a large drone even in case of a wind gust or a subsystem failure.
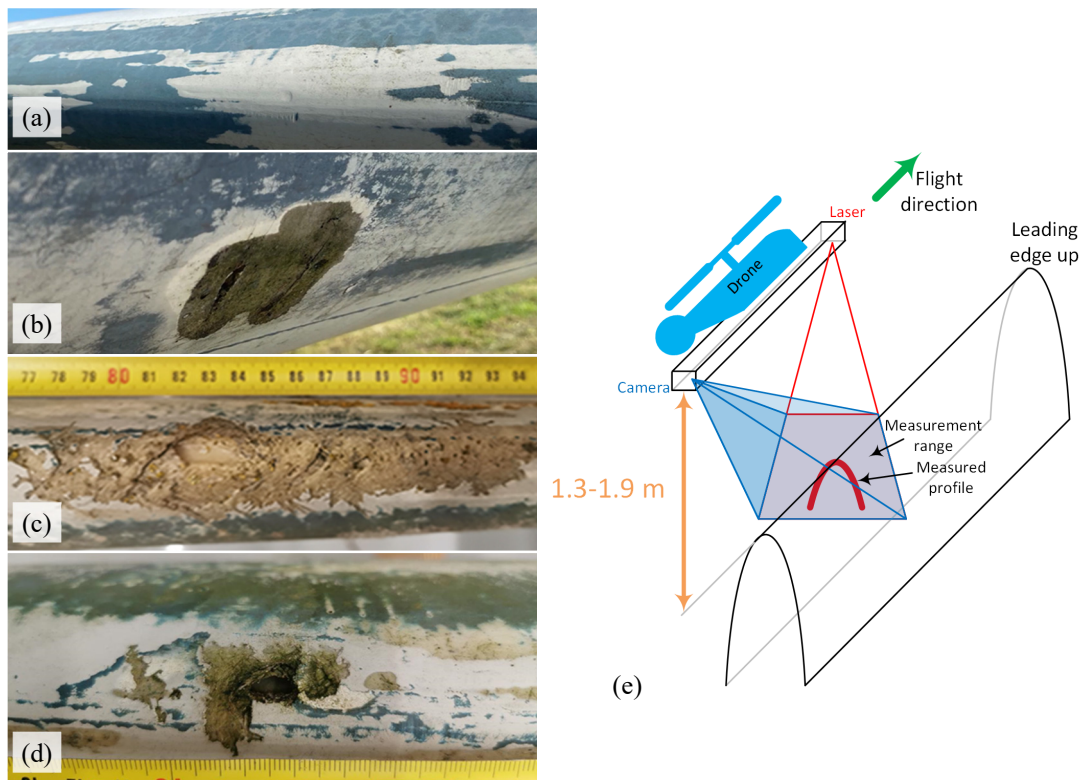

Figure 1. Real-life damage cases of a wind turbine leading edge, including (a) erosion, (b) loss of coating, (c) severe erosion, (d) probable impact or lightning damage. (e) presents the proposing drone-based measurement approach with the laser line scanner.

Current results, presented in this paper, include detection of eroded and damaged areas with a sub-millimetre resolution in the laboratory conditions on a real out-of-service blade with the sensor positioned and moved with a scanning frame. Further in the project, a custom-developed heavy drone will be used to carry the sensor to scan the blades offshore. This development is done within the smart maintenance innovation project AIRTuB: Automatic Inspection and Repair of Turbine Blades where the inspection expertise is combined with drone developers, wind-turbine manufacturers, repair and maintenance services.

2   LABORATORY SETUP FOR THE BLADE INSPECTION

A laboratory setup was developed to test the proposed measurement approach (Figure 2). A support and a scanning frames were used together to position and move the laser line scanner over a leading edge of a blade. The available 5 m tip segment of a real out-of-service blade (NedWind 40/500, originally 20 m, 22 years service life) with various surface defects was scanned and analysed.
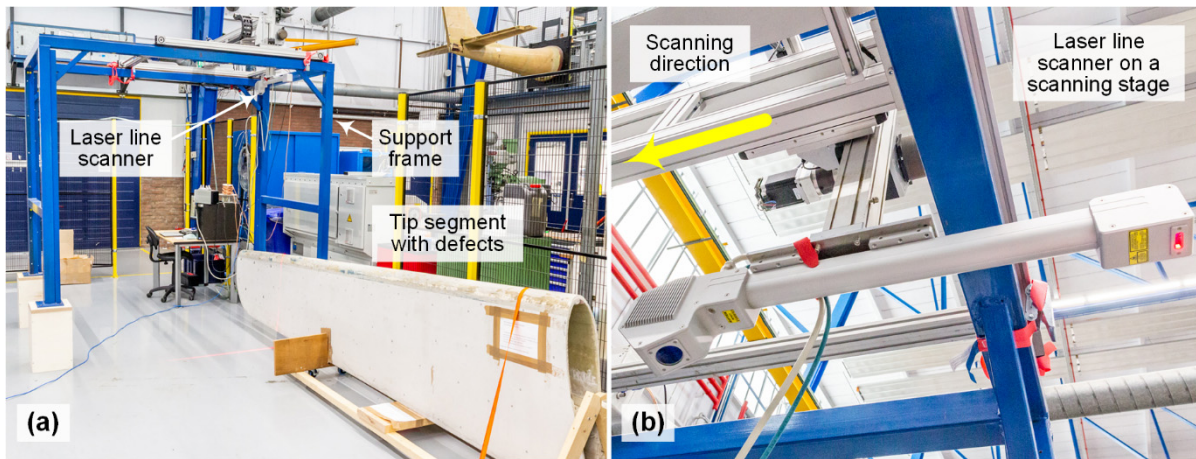

Figure 2. The developed laboratory setup for the blade inspection, including
(a) the support frame above the tip segment of a blade and (b) the custom long-range laser line scanner.

A market search showed a limited choice of long-range laser line scanners capable to work at distances from 1.5 to 2 m. Therefore, a customized long-range laser line scanner RF629 was developed by Riftek, Belarus with a measuring range of 490 mm (width) at 1310 mm (distance from the sensor) and 680 mm at 1900 mm. The extended measuring range resulted in an elongated sensor design with an overall length of 680 mm. The sensor has 1280 points (pixels) across the horizontal measuring range operating at 2 kHz which is sufficient to form a uniform dense point cloud at the flight (scanning) speed around 0.5-1 m/s. The total sensor error of the distance measurement at the midrange of 1600 mm does not exceed 0.65 mm (3 standard deviations), the sensitivity is at round 0.1 mm. This combination of the sensor mass, dimensions and resolution is considered as a rational choice for this specific task.

To have a reliable representation of the sub-millimetre erosion features an additional reference laser line scanner LLT2750-100 by Micro-Epsilon, Germany was used to measure the surface shape at a closer distance of 0.5 m. The main limitation of this sensor is the measuring range at a distance of 300-600 mm, which is not realistic from the safety side of the drone-based inspection (Figure 1 (e)).

The erosion and defect detection approach used in this paper is based on deterministic analysis of the individual profiles:
- eliminating outliers from the point cloud;
- fitting a smooth curve into the filtered profile using local regression and identification of the local profile variation;
- binary thresholding deviations of 0.2 mm in depth to keep the desired erosion pits of 0.3 mm, followed by image dilation and removal of deviations by the edges of the blade, where the curvature gets significant.

This deterministic approach is potentially not sensitive to drone vibrations as the individual profiles imaged with an exposure time of 2 to 5 µs are expected to be not affected by the drone vibrations.

3   EXPERIMENTAL RESULTS OF THE LEADING EDGE EROSION INSPECTION

The tip segment of the blade that was used for this project has multiple defects, including severe damage in areas 1 and 4 (Figure 3 (a), also shown in Figure 1 (c,d)), a moderate erosion in area 2 and a healthy reference area 3. The shape of this tip segment was measured with two laser line scanners, the results for the first 1.1 m part of the blade are presented and analysed in this paper.

First, the reference deviation map was processed from the shape data obtained with the LLT2750-100 scanner by Micro-Epsilon (Figure 3 (b)). All areas of interest 1-4 can be reliably identified in the deviation map and further processed. The overall height range where the features are reliably seen is about 0.8 mm.

Second, the deviation map with the RF629 scanner by Riftek (Figure 3 (c)) was obtained. The severe damage areas 1 and 4 are also reliably identified, however, the boundaries of the moderate erosion area 2 are less clear. This directly affects the clarity of the binary defect map (Figure 3 (d)) with the global threshold of the height deviation set to 0.2 mm.

The healthy area 3 is clearly seen in the deviation maps from both sensors (Figure 3 (b-c)), also in the binary map (Figure 3 (d)). This fact defines an alternative approach to detect erosion: tracking of the healthy areas first and further evaluation of the deviating areas.
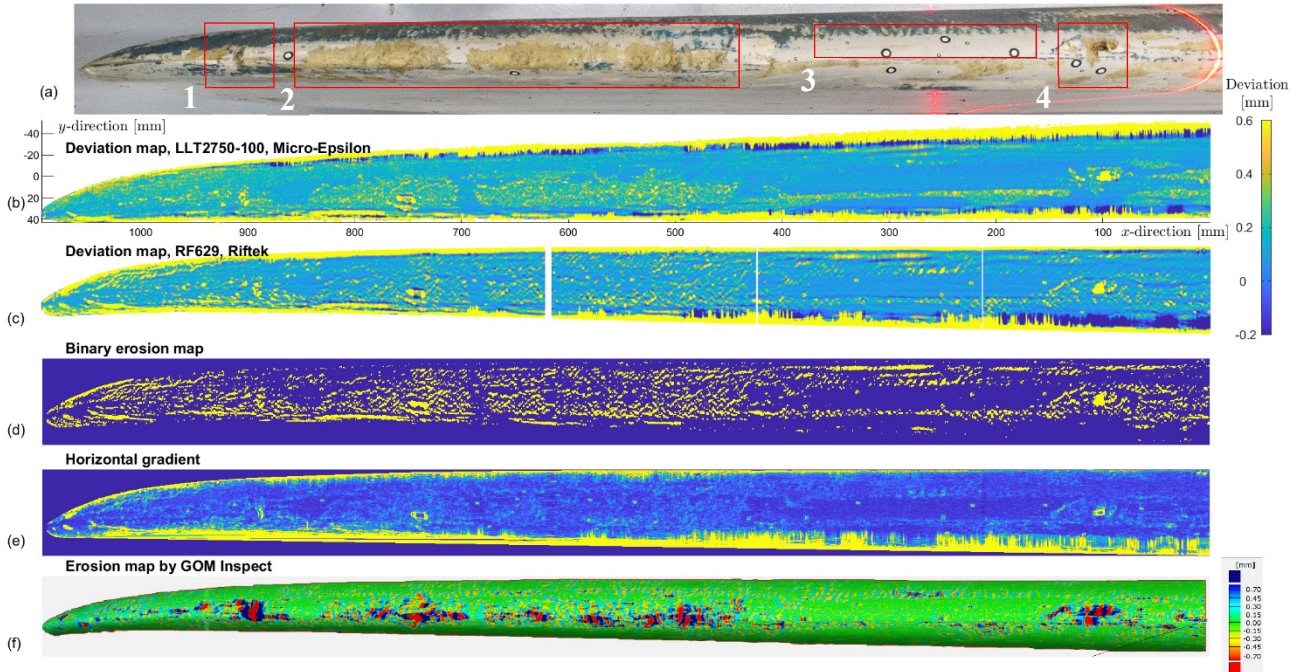

Figure 3. Overview of the experimental results (a) with the tip section of the blade, (b) the deviation map based on the shape measured with the LLT2750-100 scanner by Micro-Epsilon, (c) the deviation map based on the shape measured with the RF629 scanner by Riftek. The deviation map (c) was further processed to give (d) the binary erosion map and (e) the horizontal map gradient, and (f) the surface defect map based on the shape measured with the RF629 scanner processed by the GOM Inspect software.

The severe damage areas 1 and 4 scatter back a limited amount of the laser light and cause issues with the defect contouring. The image derivative in the horizontal direction (Figure 3 (e)) was identified to provide reliable contouring in addition to the binary map (Figure 3 (d)).

To benchmark the developed deterministic approach of individual profile processing, the pointcloud acquired with the RF629 sensor by Riftek was processed with GOM Inspect software to estimate the surface defect map (Figure 3 (f)) by

fitting a 3D smooth surface into the pointcloud and calculating the deviation, which is a proprietary algorithm. The calculated erosion map shows a clear identification of the areas 1 and 4, also the area 2 with moderate erosion.

Comparison of the individual profile processing (Figure 3 (c-e)) and the full 3D fitting (Figure 3 (f)) shows that the 3D fitting is more reliable in the upper and lower sides of the blade where the surface curvature is significant. Processing of the individual lines shows reliable deviation maps close to the center of the leading edge, while at the top and bottom sides (Figure 3 (c-e)) the individual fitting is less reliable.

4   CONCLUSIONS

Quantitative characterisation of the leading edge erosion of wind turbine blades, especially in an open environment and especially offshore, is a challenging task that has not been fully addressed yet. The requirements can be formulated as a blade surface shape measurement at a distance of 1.5 to 2 m with a sub-millimetre resolution (towards 0.1 mm) from a drone. The first literature results [17-19] use drone-based photogrammetry and the structure-from-motion approaches. In this paper, we have presented an alternative solution based on a long-range custom made laser line scanner. The processed local deviation maps (Figure 3 (c-f)) provide reliable identification of the areas with severe damage and with the healthy coating. The first experimental results with the areas with moderate erosion and minor erosion pits show that the erosion areas can be identified, however further processing (including decreasing false positives, joining of the scattered erosion parts into erosion clusters) can improve the inspection outcomes. Later the developed deterministic approach will be benchmarked with machine learning capabilities.

We expect a quantitative inspection of the current erosion state and long term degradation monitoring to provide crucial information for wind farm maintenance. The inspection results may coordinate the recoating program for a specific blade. In addition, the transfer from the current corrective (reactive) blade maintenance to the condition-based and predictive maintenance [20] also depends on reliable inspection.

Future steps in the AIRTuB project include integration of the laser line sensor in the drone, hangar flight tests and a series of offshore inspections.

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