Increasing Economic Viability and Safety Through Structural Health Monitoring of Wind Turbines

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***Abstract*—Serious accidents with property damage or even human casualties, result from structural flaws in wind turbine rotor blades. Common maintenance practices result in long downtimes and do not lead to the required results. Therefore, the Ruhr West University of Applied Sciences and the iQbis Consulting GmbH, currently research a new structural health monitoring method for wind turbine rotor blades. The goal of this project is to build a sensor system that can detect structural weaknesses inside of rotor blades without the need of downtime for industrial climbers. This technology has the potential to prevent accidents, save lives, extend the useful life of wind turbines and optimize the production of green energy.**

Keywords—Condition monitoring; Wind energy; Preventive maintenance; Infrared imaging

I. INTRODUCTION

Wind turbine power plants are, among all the competitors in the green energy business, a simple, effective and technologically mature way of producing renewable energy. This way of harvesting energy proved to be very profitable and the development of new and bigger wind turbines is still ongoing. Modern power plants have rotor diameters in excess of 100m. While the enormous size has advantages in energy conversion, it makes monitoring and maintenance complex and work intensive.

Like any structure that is exposed to the elements and is subjected to very high loads, wind turbine rotor blades develop material fatigue. The resulting long-term damage is often hard to detect before leading to catastrophic failures.

In 2016 alone there were 37 accidents due to blade or structural failures, with an additional 13 till march 2017 [1]. Apart from the obvious economic losses, due to downtime and repair charges for damage on the plant and the surrounding environment, there have also been tragic cases of fatalities. Accidents and their resulting costs can often be prevented with proper maintenance.

The biggest part of the operating expenses of wind farms are for up-keeping and repair [3]. The amount varies depending on the location of the plants. If they are build offshore the costs for maintenance rise enormously.

II. STATE OF THE ART

As of today industrial climbers, who examine them haptically and optically, conduct the monitoring of wind turbine rotor blades. This way of inspection is cost intensive and dangerous, while on the other hand produces only insufficient results. A decision of a German court even stipulates that this is not an appropriate way of maintaining rotor blades [4].

There are ambitions to develop structural health monitoring (SHM) systems, which can make a qualified statement about damage inside the rotor blades. Therefore, various scientists perform research on different testing methods:

A. Acoustic Emission

When damage in rotor blades occurs, it produces sounds, which can be detected by sensors attached to the blades. It has been shown that even small cracks can be located by these sounds [2]. Theoretically, this is a good method for long-term monitoring, but it only works if the damage occurs while the sensors are attached. It can also not be used to detect existing damage.

As the system needs to be permanently attached to the rotor blades, it is only interesting for newly manufactured units. For existing wind turbines this method is not suitable.

B. Ultrasonic

By sending ultrasonic waves through the rotor blade cracks can be detected. The waves pass through the material and are partly reflected. If cracks exist, the returned signal gets mode changed and the damage can be located. The downside of this method is that only cracks which lie perpendicular to the ultrasonic waves, can be found [2].

While actual products using ultrasonic exist the use is limited. Due to the small field of view of the sensors, many are needed to capture the whole rotor blade. Therefore, the examination with ultrasonic sensors requires excessive downtime and is expensive.

C. Thermography

Using infrared imaging of the rotor blades, their inner structures can be revealed. Damaged regions show different thermal responses in comparison to the normal structure of a blade.

A promising approach is to use ultrasound to apply oscillating stress on the wind turbine. Cracks and voids in the inner structure can be detected in a thermographic image because they heat up differently [5]. While interesting, this

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approach suffers from the fact that the ultrasound transducers have to be attached to the rotor blades, leading to the same problem as with the methods introduced earlier.

A different approach utilizes a heat flow through an object to make its inner structure visible on the surface. This method is called active IR-thermography [6] and is often used for detecting structural weaknesses in metallic parts.

Rotor blades are mainly made from composites consisting of fiberglass, resin and wood. All these materials have significantly bad thermoconductive characteristics compared to metals. Additionally, using active devices for generating heat flow into rotor blades is impractical outside of a laboratory environment due to the large dimensions

As part of an ongoing research project to develop an on-site, non-contact SHM system, research on using the sun as single heat source for active thermography of rotor blades was conducted in laboratory experiments and validated in field tests.

III. Project scope

A. Laboratory Test

In a first step, a laboratory setup was created to examine the feasibility of this method. To achieve a manageable size of the setup, a segment of roughly 1,5 m length was cut from the outer third of an old, decommissioned rotor blade (Fig. 1).

As this segment shows no obvious damage, a 20 cm long and 3 cm wide part was cut from the adhesive joint of the spar to simulate missing glue. Such anomalies can be found in blades because of production faults. Additionally, a block of aluminum was glued to the inner surface to simulate displaced material chunks. These can be attributed to a different class of production faults. The chunks of material can break loose and crash into the hull while the rotors are spinning.

Figure 1. Rotor blade specimen

In field the only practicable heat source available is the sun. While other possibilities like strong heat lamps exist, their use is considerably more resource intensive. Therefore, using the sun would be the obvious choice if possible. The sun can not be influenced, therefore any manipulation of the heating and cooling intervals must be achieved differently.

The radiation of the sun can be seen as homogenous over the area of the rotor blade. As a result, the temperature rise of different points on the surface should only differ due to the characteristics of the rotor blade.

To emulate this behavior in the laboratory setup two IR-lamps were used to heat up the specimen from multiple directions. The lamps can be positioned freely and have the option to adjust their heating power. Therefore, it is possible to simulate different sun intensities and try to get the heating as homogenous as possible. The exact configuration of the setup is shown in Fig. 2 and Fig. 3.

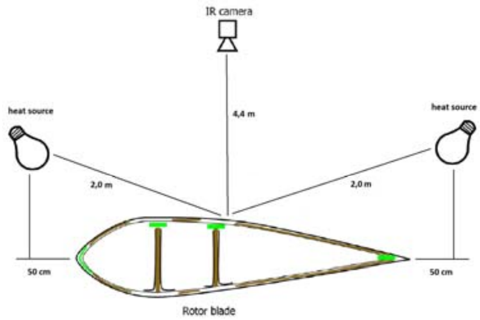

Figure 2. Sketch of the experimental setup

As a result of previous studies [7], it does not make a difference which IR-camera is used in the experiments. Despite of different thermal and picture resolutions the results are the same, as long as they operate in the long or mid wave spectrum. In the latest tests, a FLIR T640 thermal camera was used. The frequent automatic adjustment of the IR-camera can sometimes lead to calibration offsets of up to 2°C. To prevent this from happening, the automatic adjustment of the camera was disabled, accepting a small drift of the measurement.

The experiments are a continuation of previous work described in [7]. To generate a heat flow into the rotor blade, the specimen was heated up with the IR-lamps. The duration of the heating phase was adjusted to show deeper structures instead of details right beneath the surface. After turning off the IR-lamps, the heat flow naturally changes to flow out of the specimen. Ultimately, these heat flows open up the possibility to visualize the structure of the rotor blade. To monitor the results a continuous sequence of thermal images was recorded, including both the heating up and the cooling down periods.

Figure 3. Laboratory setup

B. On-site Test

To transfer the laboratory experiment onto an on-site wind turbine, the test procedure had to be modified to accommodate the conditions. The first difference is the considerably larger size of the complete wind turbine compared to the laboratory sample. As a consequence the distance between the camera and the rotor blade of the wind turbine plant is increasing as well, so a different lens had to be used. Due to availability a different camera was used in the tests, a FLIR A655sc. The resulting on-site testing setup is shown in Fig. 4.

Figure 4. On-site test setup

The heating process using the sun is not as controllable as the IR-lamps in the previous tests. As the sun can obviously not be controlled the only simple way to manage the heat flow is by rotating the rotor blade to face the sun or away from it. With the available plant, it turned out to be more controllable to rotate the wind turbine's gondola. The rotor was kept in one position using the brake (Fig. 5).

Because of the circumstances at the site, the camera has to be repositioned between the two phases. Consequently, two sequences had to be recorded instead of a single sequence, unlike the laboratory tests. This results in a loss of data while the gondola turns and the camera is repositioned.

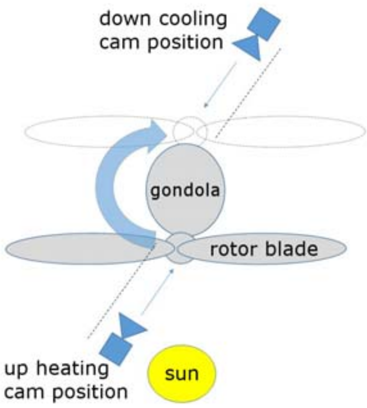

Figure 5. Sketch of on-site experimental setup

IV. RESULTS

A. *Laboratory Test*

The previous work from Fey et al [7] described the conditions under which structures can be detected through step heating. The findings from this study show that small details, adhesive joins and the general structure of the rotor blade materials can be made visible.

The goal of this study was to define a laboratory setup including a heating and cooling process that can be transferred to on-site tests. This allows testing and development of data analysis procedures with less need of expensive on-site tests.

To analyze the behaviour in detail two regions of the blade were marked in the recording. In the laboratory setup the positions of structural elements of the blade are known. To get data from different structural regions the points were chosen so that one is on a spar cap and the other is in a region with material on a wooden core. The Temperature of these Points is tracked over the complete time of the experiment and is then plotted into Fig. 6.

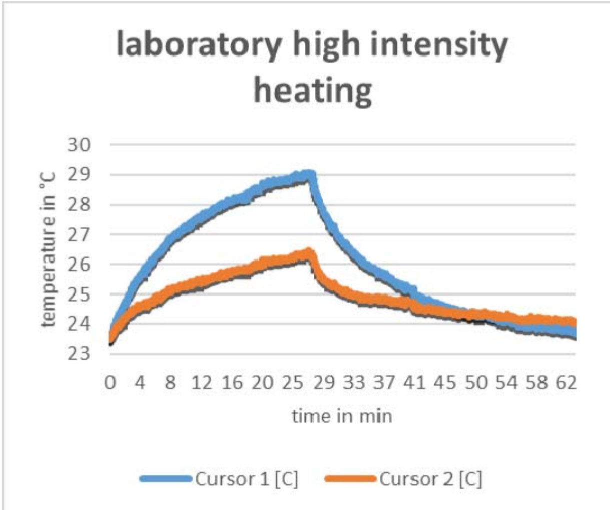

Figure 6. Temperature curve (laboratory test)

At the beginning of the experiment, both measurement points have the same temperature. The infrared image of this time stamp can be seen in Fig. 7. It shows that the temperature of the whole rotor blade is almost the same at this time. The bright areas are reflections of the IR-lamps and must be treated specially while analyzing the data.

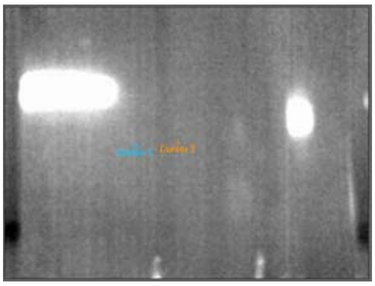

Figure 7. Start of heating process (laboratory test)

During the heating phase, the temperature of the two points is drifting apart quickly. Because the cursor positions were chosen so that the internal structures behind them are radically different, this matches the expected behavior. Additional points on the same type of structure show almost identical temperature rise but are not pictured here to improve the clarity.

The difference in the temperature rise leads to a higher contrast and therefore to a visibility of the inner structures (Fig. 8), as shown by Fey et al [7].

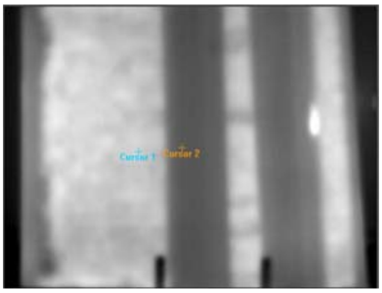

Figure 8. After turning of the IR-lamps (laboratory test)

After the lamps were switched off the direction of the heat flow inverts. At points where the temperature was rising faster during the heating phase, now a faster cooling can be observed. The temperature at cursor 1 is dropping below the temperature at cursor 2 roughly around minute 50. Fig. 9 shows an image from the end of the observation period.

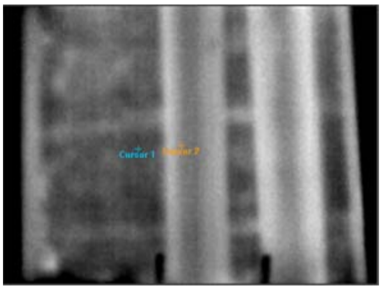

Figure 9. End of observation period (laboratory test)

B. On-site Test

Similar to the laboratory setup two points are watched over the whole experiment time and the temperature development is plotted to Fig. 10. As the internal structure of the blade is not known the points could not be selected based on the internal structure. So, two measurement points with a higher thermal contrast were chosen. As before, the comparison of points with similar temperatures reveals similar thermal behavior over time. For clarity purposes this is not depicted in the chart.

The wind turbine was in operation when the experiment was started and partly faced the sun. Getting the blade in position also took some time, so the effective start of the heating period was not observed. Due to those practical limitations the temperatures of the two points already had drifted apart at the beginning of the recording, unlike in the laboratory curve (Fig. 10).

The camera had to be repositioned after moving the rotor blade out of the sun. A continuous observation of the exact same points is therefore not possible in this particular setup, so a new set was chosen for the cool down phase in similar positions. Therefore, the temperatures at the start of the cool down phase do not match those at the end points of the heat up curves. As the automatic adjustment of the camera was turned off, the measurement was influenced by the changes of wind speed effecting the internal temperature of the camera. An example is shown in Fig. 10 from minute 49 to 56. The unexpected rise in temperature, resulting from a period of still air, can mathematically be removed using information from the built-in camera sensors.

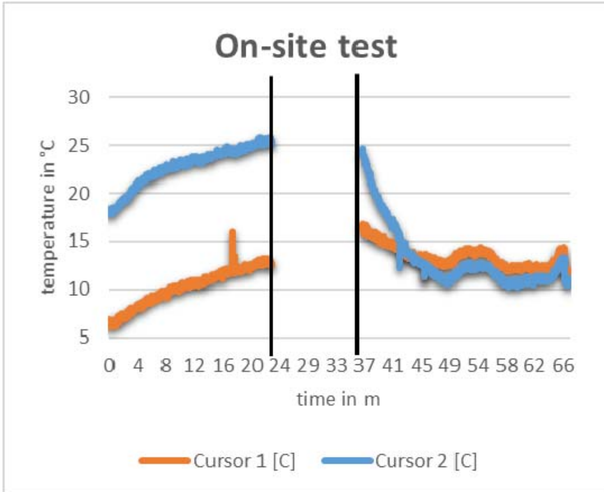

Figure 10. Temperature curve (on-site test)

Also, infrequent spikes can be found for example at minute 16 (Fig. 10, cursor 1), which arise from a parallel experiment with a drone flying along the rotor blade and therefore through the image.

Both points can clearly be distinguished from each other for most of the time, revealing internal structural features of the rotor blade.

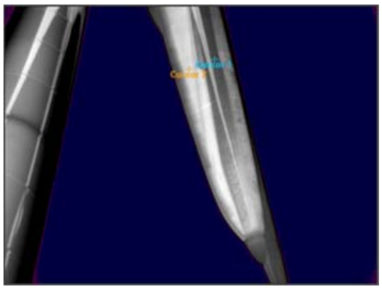

Figure 11. Start of heating process (on-site test)

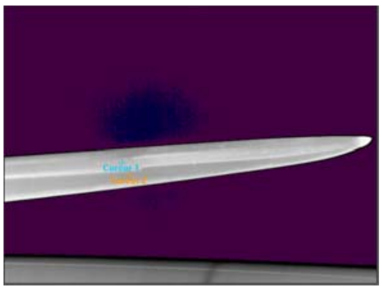

Figure 12. End of observation period (on-site test)

In Fig. 11 these structures can roughly be seen but are heavily obstructed by reflections of the sun. These reflections are not present in Fig. 12. Therefore, the structure can be better observed.

C. Comparision: Laboratory and On-site

By comparing the curves from the laboratory (Fig. 6) and the on-site (Fig. 10) tests, it becomes clear that the general behavior in both environments is similar.

In both cases, areas of high structural and thermal density clearly differ from those with lower densities in the resulting infrared image. Observing the up-heating phase, again the areas of high density differ from those of lower densities in their thermal behavior over time. Complementary behavior can be seen in period of down cooling.

In the on-site experiment, the cool down phase is easier to observe, as it is free of reflections of the sun.

D. Advantages of the new active thermography approach

Using active thermography with the sun as the only heat source to inspect wind turbine rotor comes with some benefits in comparison with the methods discussed earlier.

Regardless of type and age of the wind turbine power plant, inspections can be done by using only a single thermographic camera. Additionally, the inspection can be performed contactless from the ground. Every other method requires rather a larger number of sensors or close contact with the rotor blades. Therefore, lower costs for inspection and shorter downtimes than with those other approaches can be expected.

The structural health monitoring system can be used throughout the year as long as the environmental conditions allow the creation of a step in the heat flow.

Compared to the inspection by industrial climbers, the downtimes are drastically reduced by this method. While industrial climbers take several days to inspect the entire plant, the step heating method takes only a few hours and produces objective and storable dat3a-sets.

V. CONCLUSION

The findings of these investigations have shown that step heating active thermography using only the sun as heat source is possible. In both setups, significant comparable features can be extracted. There are difficulties that are not present in the laboratory environment, but those can be overcome. With reasonable efforts, the on-site conditions can be simulated in the laboratory, thus making further development more efficient and less expensive.

With ongoing research of the data evaluation methodology based on state of the art active thermography techniques, an efficient on-site non-contact structural health monitoring system comes within reach.

Such a system will allow cost efficient long-term monitoring of installed rotor blades with shorter downtime compared to the state of the art. Additionally it provides more significant information on the condition of their inner structures.

Serious accidents can be avoided by preventive maintenance. Probably, longer service life can be achieved thus allowing more sustainable operation of wind farms, which seems to be strongly needed while wind turbines grow in size and numbers.

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