



Thermographic rotor blade inspection from larger distances – a promising tool for the maintenance of wind turbines

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Abstract. The permanently increasing number of wind turbines requires suited inspection and monitoring methods to ensure liability and security. Concerning the inspection of rotor blades, only manual inspections are state of the art. Thermographic Testing (TT) has the potential to detect typical failures and damages on rotor blades. The paper presents some results of onsite measurements carried out as “passive thermography”, i.e. without a defined heating procedure. Due the totally contactless measurement principle, TT can be applied to rotating blades as well as to resting blades. Both methods will be compared with respect to their possible realization.

1. Introduction

The increasing number of installed wind turbines onshore as well as offshore requires permanent growing resources to ensure the availability for electric power generation. The turbine rotor blades are one of the most stressed components of a wind turbine, and the trend to longer blades beyond 50 meters leads to increasing loads. The standard inspection procedure is performed visual and by coin-tap, which requires highly trained staff, special equipment, and that the turbine is switched off. In order to reduce a direct access to the particular blades, an inspection method is needed that works at longer distances. In addition to the installation of Condition Monitoring Systems (CMS), a suited tool could be provided by camera inspections by means of photo cameras as well as infrared cameras. Although the onsite thermographic inspection of rotor blades was already presented in 2006 by Meinschmidt and Aderhold [1], almost no further development or observation results have been published so far.

This paper presents some selected results from the research project “IKARUS” standing for (German) “Infrarot-Kameratechnologie zur berührungslosen Analyse von Rotorblättern unter Hoch-See-Bedingungen”; (Engl.) “Infrared-camera technology for the non-contact Analysis of Rotor blades under Open-Sea-Conditions”). The main goal was the evaluation of Thermographic Testing (TT) as an inspection method for wind turbine rotor blades, which can be applied at farther distances.

The usual procedures in TT contain a controlled generation of a thermal disequilibrium inside the object under test (OUT), which is not practicable for rotor blades due to



their large size and uneven shape. Thus, passive thermography [2] investigations were the main issue within the project. The next figures (1, 2 and 3) show a typical measurement constellation and thermograms which can be obtained using state of the art equipment.



Fig. 1: onsite investigation of a rotating wind turbine at sunny weather, distance of about 250 m to the hub



Fig. 2: stopped wind turbine during maintenance inspection using a special platform

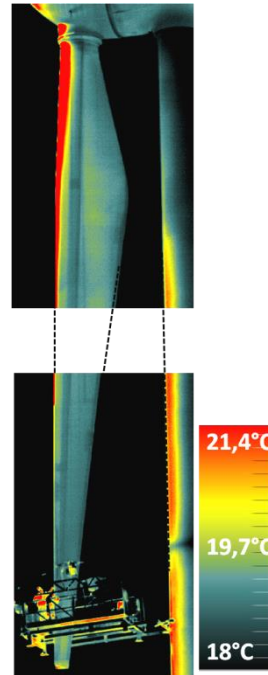


Fig. 3: thermograms of the lower rotor blade shown in fig. 2, recorded with an Infratec 8300 camera (see following section Experimental details)

It should be emphasized that the surface of such extended objects can only be entirely warmed up in a homogeneous way by the sun or by a homogeneous thermal background. Therefore, the ASTM D4788 – 03 describes a thermographic test method for bridge decks based on solar heating [3]. However, not only solar heating but also convective and radiative effects from the surrounding were considered within the project.

2. Principle of thermographic testing of rotor blades

The general principal of thermography is based on the thermal behaviour of an OUT which is in thermal disequilibrium with its surrounding. This disequilibrium leads to heat transfer processes inside the OUT after the energy input. Among other factors, these transfer processes are influenced by geometrical features like thickness and shape as well as by the material properties density, specific heat capacity and thermal conductivity. A detailed description of the involved physical processes can be found in standard textbooks i.e. [4, 5]. Both, geometrical features and differing material properties have to be considered when TT is applied on wind turbine rotor blades.

The following Fig. 4 displays the principal structure of a rotor blade in cross section view. Mostly, the blade consists of two half shells connected by adhesive bonds at the leading edge and the trailing edge. The inner beam structure strongly enhances the mechanical strength. It is also fixed by adhesive bonds. Both kinds of adhesive bonds (red highlighted in Fig. 4) are essential for function and durability of the rotor blade. Possible detachments

or gaps inside the glue layer are more or less laterally extended i.e. parallel to the surface. Thus, TT should be a suited NDT method, if the depth is not too large.

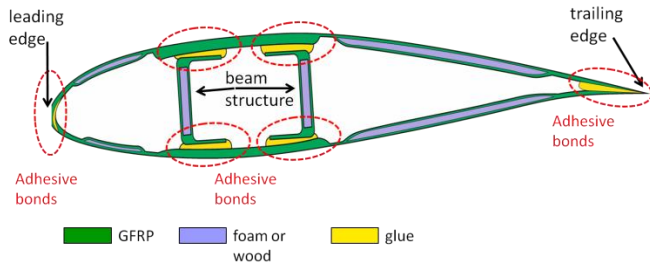


Fig. 4: scheme of the cross section of a rotor blade, different materials are displayed with colors

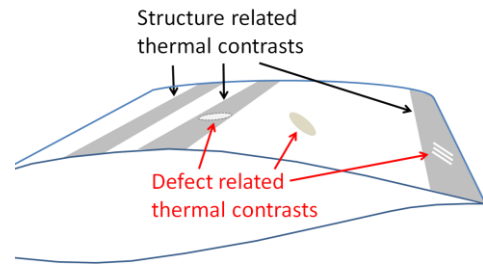


Fig. 5: thermal contrasts to be expected at a rotor blade after external heating or cooling

Those parts of the outer shell, which are in contact to backside glue layers, behave thermally like parts of larger thicknesses (i.e. like regions with enlarged thermal capacity) leading to the formation of thermal contrasts after external heating or cooling. Fig. 5 shows the corresponding thermal contrasts as grey colored stripes, indicating how thermograms of a rotor blade usually look like. If inner defects existed they would cause additional thermal contrasts overlaying the thermal signature of an undamaged blade. Some examples are drawn in Fig. 5 (red arrows and text). Careful inspection of Fig. 3 reveals stripe-shaped thermal contrasts comparable to the drawing in Fig. 5. Another example is shown here in Fig. 7:

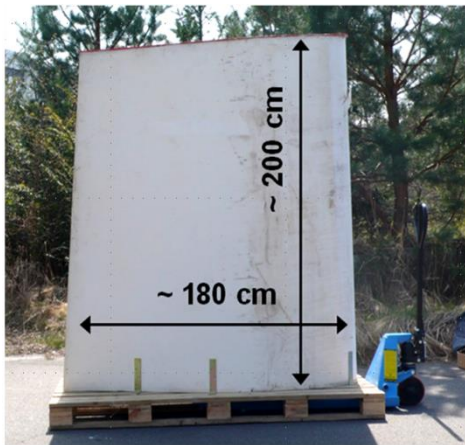


Fig. 6: separated part of an used rejected wind turbine rotor blade mounted on a pallet for outdoor measurements

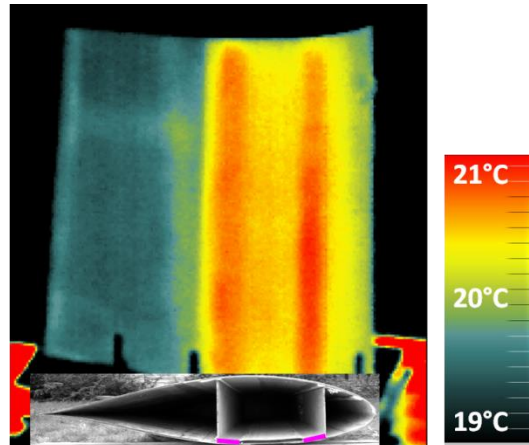


Fig. 7: thermogram of the blade part recorded in a distance of 34 m after a sunny summer day (for details see [6]), adhesive bonds corresponding to the recorded surface are magenta highlighted in the photo of the cross section below

In this case, a separated part of a rejected wind turbine rotor blade (shown in Fig. 6) was observed with an infrared camera under different weather conditions from a larger distance [6]. Stripe shaped contrasts associated with the beam were clearly detectable but the temperature contrasts were weak, i.e. below 1 K. These examples shall only demonstrate how a thermographic inspection method could work.

3. Experimental results

Outdoor measurements were conducted in onshore wind farms by courtesy of the owner More energy GmbH. The IR camera was located at the ground in different distances to the particular wind turbine (as shown in Fig. 1). Usual distances to the rotor blades were between 150 and 300 m leading to geometrical resolutions between 2.5 cm and 5 cm per pixel. In order to avoid motion blurring effects at rotating blades only cooled infrared cameras with a snapshot mode and short integration times were applied. The following results were recorded with the ImageIR 8300, equipped with an objective of 100 mm focal length. In the following, some results are discussed for the case of rotating blades of an operating wind turbine, and for the case of inactive blades of a turbine that was switched off.

3.1. Rotating blades

The following figure 8 contains thermograms of all three blades of a turbine during operation, which was running with 15 rotations per minute. Here, the suction sides were observed while the sun was shining mostly on the pressure sides. The accurate sun position can be approximated by considering the location of the heated parts of the wind turbine (strong red regions in the thermograms).

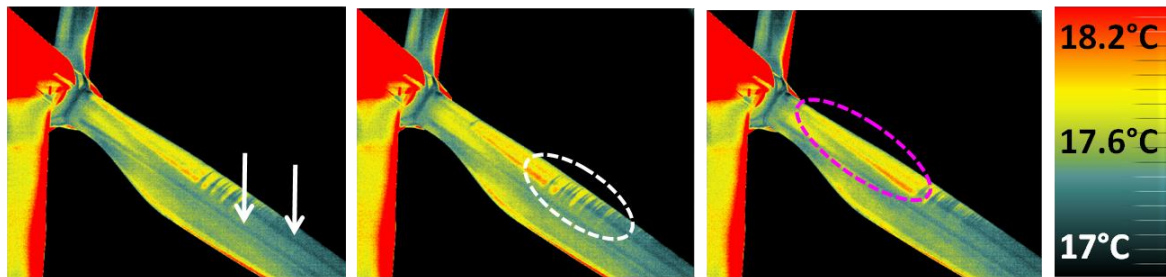


Fig. 8: thermograms of all three rotor blades of a rotating wind turbine in the morning, temperature scale is optimized for the blade regions, arrows mark stripe-shaped contrasts correlated to an inner structural feature, the white ellipse includes an uneven stripe pattern due to the occurrence of turbulent wedges at the surface, the magenta ellipse includes a moderate heated region caused by laterally incident sun rays

All thermograms exhibit three striking features:

- Two long parallel cooler stripes (white arrows pointing to dark blue stripes) probably due to interior belts or adhesive bonds
- Uneven stripe pattern at the leading edge due to the occurrence of turbulent wedges at irregularities on the surface i.e. bumps or open cracks [7]
- Partly warmer region at the leading edge near the hub, probably caused by partly incident rays of the sun which is located laterally with respect to the curved shape of the blade

Since there was no direct sun exposure, the parallel cool stripes must have been generated by a former increase of the air temperature during the morning (about 3 K within 3 h). Faced with a variety of thermal contrasts with different causes, it becomes difficult to identify contrasts which are related to internal defects. Furthermore, detecting small thermal contrasts of relevant defects can be hindered when they are masked by greater thermal contrasts of disturbing reflections/radiation. However, one gains more clarity on the interpretation of thermal contrasts by comparing the particular thermograms with each other. Within the project IKARUS, a simple difference method was considered in more detail [8]. In

order to achieve thermograms with blades in exactly the same orientation a digital post processing was carried out using usual image processing tools. The developed software solution provides the following data processing steps automatically:

1. Separating thermograms of blades only within a predefined angular range
2. Re-sorting the thermograms into three new sequences related to each blade
3. Selection of thermogram pairs with most similar blade orientations
4. Correction of the remaining angular misalignment by means of an image registration procedure
5. Compilation of new sequences for each blade pair containing the best difference images

Performing this data processing resulted in a set of difference thermograms shown here:

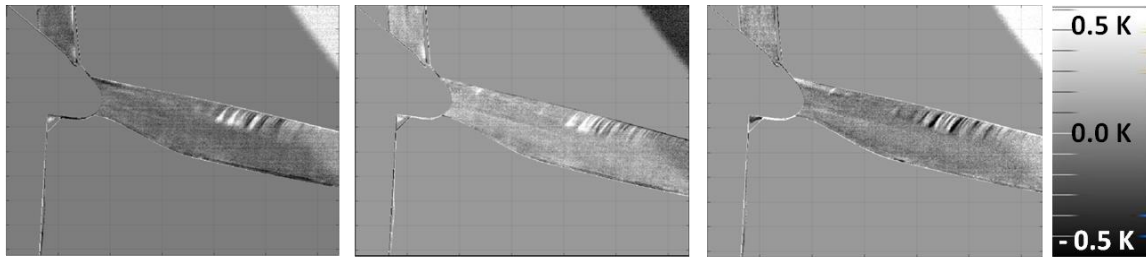


Fig. 9: difference thermograms of the rotor blades shown in Fig. 8, every thermogram represents the spatial distribution of thermal differences of two different blades (left: blade 1 - blade 3, centre: blade 1 - blade 2, right: blade 3 - blade 2)

As to be expected, the structural related parallel stripes and also the (disturbing) warmer region at the leading edge disappeared in the difference thermogram, because the geometrical shape is more or less equal in all blades. Only the turbulence wedges remain and actually increase in number, because the difference thermogram contains thermal signatures of two blades with each particular turbulence patterns. Depending on whatever is minuend or subtrahend within the calculation of the difference thermogram, the thermal contrasts associated with turbulence wedges appear with different signs.

Summarizing, difference thermograms can facilitate the detection of thermal irregularities in rotor blades by minimizing/eliminating disturbingly masking features such as inner structures or radiated regions. Yet, in regions where turbulence wedges evolve (in case of rotating blades), the detection of possible inner damages is hindered. The investigated wind turbine, here, has no known damages which could be presented in Fig. 9.

Alternatively, thermal rotor blade inspection can be carried out when the turbine is in shut down modus as shown in Fig. 2 (where no turbulence wedges should appear)

3.2. Blades at a standstill

Fig. 10 and Fig. 11 display again thermographic results obtained at the wind turbine shown in Fig. 2. The different temperature scales indicate a typical problem of non-rotating blades: inhomogeneous heating of the very uneven-shaped blade surface leads to high temperature contrasts that are much stronger than possible defect related contrasts.

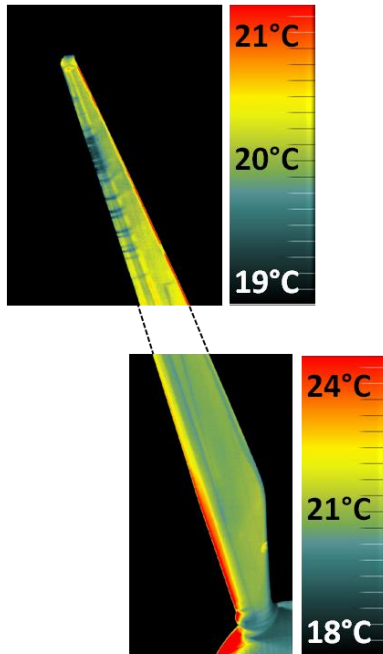


Fig. 10: thermograms of the upper rotor blade above the nacelle (not shown in Fig. 2) with adapted temperature scales

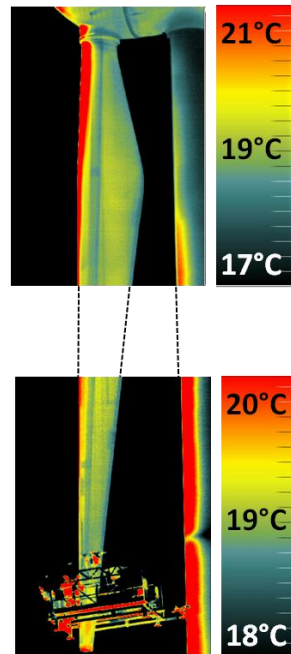


Fig. 11: thermograms of the lower rotor blade below the nacelle (as shown in Fig. 2) with adapted temperature scales

However, blade regions with nearly homogeneous surface heating exhibit very clearly structure correlated contrasts. Interestingly, turbulent wedges appeared also in this case at the upper half of the upper rotor blade resulting from the actual wind flowing around the resting blade. Concerning convection effects, it must be generally noted that the strength of the particular thermal contrasts depends not only of the velocity difference between air and blade surface, but also from the temperature difference (sign and magnitude) between air and blade and the actual exposure to sunlight. Of course, the probability of thermal active turbulent wedges is strongly reduced for non- rotating blades. Furthermore, the probability increases with a higher rotation speed. In fact, there are always turbulence wedges near the blade tip of rotating blades due to the high tangential velocity in this blade sector, even at low rotating frequencies.

4. Discussion

Thermographic inspection of wind turbine rotor blades can be performed in two different ways: at rotating turbines during operation as well as at resting turbines. It is worth to compare both methods with respect to the intended application: establishing a NDT-method for rotor blades at larger distances, i.e. without the need of a direct contact to the particular blade. The following comparison contains an evaluation according to a 5 points system (-2 not suited ... +2 fully suited) including some comments.

Table 1: comparison of the suitability of thermographic inspection applied on non-rotating blades (resting wind turbine) and rotating blades (wind turbine in operation)

critierion	non-rotating blade	rotating blade
Homogeneous solar heating of all blades	-1 not possible at higher solar altitudes	1 size of heated regions depends on the rotor orientation in relation to the sun position
Signal enhancement via comparison of all blades	-2 not possible due to inhomogeneous heating and reflections from the environments	2 no restriction at all
Disturbing thermal active turbulence wedges	2 low probability	-2 probability increases strongly with rotation speed, inspection of blade tips is hindered
Focussing of IR-camera optics	2	-1 restricted to the hub only
Technical requirements for IR-camera	1 uncooled system with large integration time is sufficient	-1 Short integration is required to avoid motion blurring
Distance to the blade	2 no restrictions	-1 safety distance is required because of wakes esp. in case of airborne inspections
Needed inspection time and down-time of the turbine	-2 long for all blades (moving of camera or blades is needed)	2 short
Coordination with operator	-2 definitely in all cases	0 needed at higher wind velocities, slow down of rotation is beneficial in all cases
Sum	0	0
conclusion	well suited for suspicious findings	well suited for regular monitoring

5. Conclusion and outlook

In summary, TT was considered as an inspection method for rotor blades mounted on a wind turbine, i.e. during the lifetime of a wind turbine. Here, thermographic investigations were carried out on rotating turbines as well as on resting turbines. Both methods have pros and cons. Generally, measurements at rotating blades allow a direct comparison of all

blades with each other leading to an effective suppression of disturbing contrasts. On the other hand, this mode is suffered by convection effects due to the interference between wind and rotor blades. A first evaluation of both methods was presented, resulting in stand-off.

Thus, there is a need for additional research work focused on the direct comparison of both methods applied at the same wind turbines under various weather conditions. Further, the occurrence of turbulence wedges is not only a disturbing effect, but can also be regarded as a monitor for small geometrical changes at the blade as indication for running damage processes [7]. Probably, all these approaches might be combined to reach the goal of a useful NDT method from farther distances.

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