Calculation of the power output loss based on thermographic measurement of the leading edge condition

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Abstract. Due to operation under harsh conditions, rotor blades suffer from soiling and erosion of the leading edge, which causes a premature laminar-turbulent transition of the boundary layer flow. A quantification of both the extent of the contamination and the impact on wind turbine performance is difficult and calculations are based on estimates. A new method for assessing the power output loss due to leading edge contamination is presented. The method is based on thermographic flow measurements along the rotor blade and the automated determination of the laminar-turbulent transition location. A comparison with the expected natural transition of the clean rotor blade position enables the extent of the leading edge contamination to be quantified. Measurements on a multi-MW rotor blade indicate a contamination level of up to 90.4 % in the given highly contaminated example. This information is then used in a blade element method (BEM) model to calculate the annual energy production (AEP) for both a clean and a contaminated case. Results indicate that for this particular case, the measured contamination level leads to a decrease in annual energy production of 4.7 % to 2.7 % for the investigated average wind speeds of 6 m/s to 9 m/s.

1. Introduction
The leading edge condition of rotor blades has a direct effect on the boundary layer flow, and thus affects performance and acoustic emissions. Surface contamination can trigger an early laminar-turbulent transition [1]. Although the leading edge contamination is known to have a significant effect on wind turbine performance [2], an automated quantification of the leading edge contamination is missing. To determine the rotor blade surface condition, a semi-automated contactless measurement method is developed, which is based on the thermographic determination of the laminar-turbulent transition location [3, 4]. The extent of leading edge contamination is calculated by comparing the natural transition location with the actual transition location influenced by local leading edge surface imperfections. Strictly speaking, it is not the leading edge contamination itself that is measured, but its effect on the boundary layer flow. After transforming the imaged flow data to the local geometry of the rotor blade, the chordwise extent of leading edge contamination is obtained for individual rotor blade sections. The new method is demonstrated on the rotor blades of a 1.5 MW General Electric (GE) wind turbine with a rotor diameter of 77 m. The impact on the annual energy production (AEP) is...
evaluated using a Blade Element Momentum (BEM) model that utilises modified aerodynamic polar data to reflect the leading edge contamination.

2. Measurement Approach and methods

2.1. Thermographic flow visualization

Thermographic flow visualisation measurements of the wind turbine in operation are performed in order to determine the position of the actual and the natural laminar-turbulent transition, respectively. The transition location of the clean blade is considered to be the natural transition position, as opposed to a premature transition that is forced by additional roughness due to contamination and/or surface geometry changes due to erosion. Based on a temperature difference between the object and the incoming flow, changes in the boundary layer state from laminar to turbulent can be distinguished by measuring the surface temperature with a thermographic camera. The surface temperature depends on the local heat transfer between the rotor blade and the flow, which is proportional to the skin friction in different flow regimes [5, 6, 7]. If the oncoming air is at a lower temperature than the rotor blade, turbulent flow regions appear colder than laminar flow regions, and a distinctive pattern can be observed. Fig. 1 shows a thermographic image of a rotor blade section at a wind turbine in operation acquired by a high-speed, actively cooled thermographic imaging system.

The visible turbulence wedges at about \( y = 5 \) pixels and \( y = 560 \) pixels are evidence for an early laminar-turbulent transition due to erosion or soiling of the rotor blade surface at the leading edge. The chordwise temperature profile as well as the temperature gradient for the position \( x = 500 \) pixels is depicted in Fig. 2. At \( x = 500 \) pixels, the leading edge and the trailing edge at \( y = 21 \) pixels and \( y = 212 \) pixels can be clearly identified in both the temperature profile and the temperature gradient due to the significantly colder background. The major temperature change in the transition region leads to an absolute maximum of the temperature gradient. The position of the maximum in the temperature gradient is the measure for the laminar-turbulent transition position and can be used for an automated evaluation of the thermographic images [8, 9, 10]. The example shows that both the temperature profile \( T(y) \) and the temperature gradient \( \frac{dT}{dy} \) are suitable for the localisation of the laminar-turbulent transition [3].

![Thermographic image](image)

**Figure 1.** Thermographic image of a rotor blade section at a wind turbine in operation. The laminar-turbulent transition can be identified by a significant change in temperature between the laminar and the turbulent flow region. The laminar flow region appears hotter (lighter) than the turbulent flow region. The dashed line indicates the position \( x = 500 \) pixels, for which the measured chordwise temperature profile is shown in Fig. 2 as an example.
Figure 2. Temperature profile $T(y)$ and the corresponding temperature gradient $dT/dy$ in the flow direction at position $x = 500$ pixels. The laminar-turbulent transition causes a significant temperature change in the temperature profile. This leads to an absolute maximum of the temperature gradient in the transition region.

An interpolation approach based on the approximation of the temperature profile with a Gaussian cumulative distribution function in the transition region allows the localisation of the laminar-turbulent transition in the thermographic image with subpixel accuracy [3]:

$$
\hat{T} = \hat{a} \text{erf} \left( \frac{y - \hat{b}}{\sqrt{2} \hat{c}} \right) + \hat{d},
$$

with the fit parameters $\hat{a}$ for the maximum height, the $y$-position of the turning point $\hat{b} = y_{\text{tr}}$, the width, i.e. the standard deviation, $\hat{c}$ and the offset $\hat{d}$. For the localisation of the laminar-turbulent transition, the position $\hat{b}$ of the turning point of the Gaussian cumulative distribution function is defined as the laminar-turbulent transition position $y_{\text{tr}}$. The evaluation of the temperature profile in the flow direction enables the localisation of the relative actual transition position $p_{\text{tr,act}}$ along the span at $j = 1, ..., J$ columns in the thermographic image:

$$
p_{\text{tr,act}} = \frac{1}{J} \sum_{j=1}^{J} \frac{y_{\text{tr},j} - y_{\text{LE},j}}{y_{\text{TE},j} - y_{\text{LE},j}},
$$

with $y_{\text{LE}}$ and $y_{\text{TE}}$ as the positions of the visible leading edge (LE) and trailing edge (TE), also determined by the approximation of the temperature profile with a Gaussian cumulative distribution function. The actual transition position $p_{\text{tr,act}}$ includes the transition shift by turbulence wedges due to local imperfections of the rotor blade surface. In order to gain information about the leading edge contamination, the natural transition position $p_{\text{tr,nat}}$ is additionally determined by a weighted linear least squares approximation of the actual transition positions $p_{\text{tr,act}}(j)$. Due to the weighting of the linear approximation, the influence of the wedges is drastically reduced and the transition position without turbulence wedges can be determined. An example for the results of the image processing is shown in Fig. 3.

The position of the laminar-turbulent transition in the thermographic image is then transformed to the rotor blade geometry using the known distance between the measurement position and the wind turbine rotor blade as well as the rotor blade pitch angle. With the
known distance and pitch angle, a series of coordinate transformations is carried out to enable
the determination of the viewing angle. The consideration of the position of the transition in
the image plane of the thermographic image allows the determination of the position on the
rotor blade surface and subsequently the projection of this position onto the rotor blade chord.
For this purpose, geometric measurements with a laser scanning system on a rotor blade of the
type LM 37.3p are performed. The rotor blade belongs to a 1.5 MW GE wind turbine with a
77 m diameter rotor. The geometric measurements provide the coordinates of 5 discrete sections
of the rotor blade at the radial positions \( r_i \), \( i = 1, \ldots, 5 \) [11]. The individual blade sections are
shown in Fig. 4. As a result of the geometric transformation, the chordwise positions \( P_{tr,act} \) and
\( P_{tr,nat} \) of the actual and the natural laminar-turbulent for the specific rotor blade sections are
obtained. The geometrically mapped positions \( P_{tr,act} \) and \( P_{tr,nat} \) of the natural and the actual
transition can now be used as an input for the evaluation of the aerodynamic impact by Xfoil
simulations. Furthermore, a leading edge contamination level can be specified by the comparison
of both the actual and natural transition positions and expressed by the relation:

\[
LEC = 1 - \frac{P_{tr,act}}{P_{tr,nat}}. \tag{3}
\]

The \( LEC \) value represents the difference between the natural and the actual transition position
normalised to the natural transition position. A \( LEC \) close to 100 % indicates an almost
completely tripped boundary layer flow. A \( LEC \) of 0 % indicates an actual transition position
without turbulence wedges that matches the approximated position of the natural transition.
In addition to being used for the AEP analysis, the \( LEC \) value can be used more generally to
compare different leading edge cases.

2.2. Construction of the baseline BEM model
A baseline BEM model for the GE 1.5 MW wind turbine was constructed using the open-source
code Qblade (v0.96) [12]. The following available correction models were activated in Qblade:
Prandtl tip and root losses, and 3D polar corrections. The 3D correction model used can be
found in [13]. The blade geometry obtained from the previously-described measurement process
was used to define the blade shape. Five aerofoil profiles from the blade were tested at Deutsche
WindGuard’s aeroacoustic wind tunnel, in both clean and leading edge tripped conditions using
zig-zag tape, positioned at \( y/c = 0.05 \) on the suction side and \( y/c = 0.10 \) on the pressure
side. The zig-zag tape thickness was 0.205 mm for aerofoil sections \( r_3 \) to \( r_5 \) and 0.255 mm for
section \( r_2 \). Additionally, 0.4 mm thick zig-zag tape was positioned on the two outer sections at
\( y/c = 0.50 \) pressure side, whereas it is 0.5 mm thick on the real rotor blade. Without the zig-zag
tape, the boundary layer flow may be fully laminar causing a tonal noise.
Figure 4. Individual blade sections of the rotor blade of the type LM 37.3p at the radial positions $r_i, i = 1, ..., 5$ measured by a laser scanning system [11].

The measured aerodynamic polars were imported into Qblade and used for further analysis. The turbine rotor rpm was measured during the field thermography campaign and this data was used to create a wind speed vs. rpm curve for use in the simulation. The baseline BEM calculations were carried out using wind tunnel data, and for the leading edge contamination cases the aerodynamic polars were modified using the Xfoil-calculated deltas. The baseline BEM power curve values were within 10% of those seen in field test data for this turbine for the wind speeds used for analysis in this paper. This level of agreement is considered acceptable because the focus of this study is on calculating representative performance deltas, not trying to create the most representative turbine model for comparison to field data. A second baseline model was created using the same blade shape and turbine operating parameters, but by exchanging the outer three clean aerofoil polars that represent roughly 50% of the blade length (over 60% of the swept surface) for the leading edge tripped aerodynamic polars. Due to the low leading edge contamination level present in most rotor blade root regions, the difficulty of measuring thick aerofoil sections in the wind tunnel, and the associated uncertainty in measured performance, it was decided not to include the inner two aerofoils in their tripped state. The AEP was calculated within Qblade using a Weibull k-factor of 2 and average wind speeds of 6 m/s, 7.5 m/s, 8 m/s and 9 m/s. When the outer aerofoils were fully tripped the calculated AEP loss compared to the clean blade was between 6.1% and 3.9% for average wind speeds from 6 m/s to 9 m/s, respectively. The relatively low impact on the AEP is due to the fact that the change in $c_L/c_D$ due to the tripping (or the contamination of the rotor blade) primarily affects the energy production in the partial load range. This procedure is assuming that the rotor blade condition does not change throughout the year. This is neither true for erosion, which only increases, or for leading edge contamination, which varies and can be reduced by rain during operation. However, since this procedure is the industrial standard, it was adapted and extended based on real measurement data.

3. Measurement results
In order to demonstrate the leading edge condition measurement approach, field measurement results of a GE 1.5 sl wind turbine during operation are presented, cf. section 3.1. In section 3.2 the aerodynamic impact due to the shift between measured actual and natural transition positions is evaluated by Xfoil simulations and the resulting lift and drag polars are used for the determination of the AEP by the BEM model.
3.1. Thermographic measurement of the transition location

Fig. 5 shows the thermographic measurement results of two different cases of leading edge contamination. Case 1 is the thermographic image of the suction side of a relatively clean rotor blade that belongs to the 1.5 MW GE wind turbine, cf. Fig. 5(a). Fig. 5b shows case 2 with a heavily contaminated suction side. The resulting positions $P_{\text{tr,act}}$ and $P_{\text{tr,nat}}$ of the actual and the natural transition are indicated by dashed and solid lines, respectively. The evaluation takes place for each radial section. The values of $P_{\text{tr,act}}$ and $P_{\text{tr,nat}}$ as well as the $LEC$ for case 1 are summarised in Tab. 1. For case 1 there has been an additional measurement of the pressure side with a maximum $LEC$ of 3.2%. The measurement of the pressure side is not shown, but considered in the following evaluation of the AEP. The transition location measured in case 1 is assumed to correspond to the natural transition location. It is unknown to the authors if the surface roughness of this blade has varied since its manufacturing date, and therefore the leading edge contamination level $LEC$ is measured in relative terms.

Table 1. Leading edge contamination level ($LEC$) for case 1 at 5 radial positions $r_i$, $i = 1, ..., 5$ with known geometry based on the comparison of the actual and the natural transition positions $P_{\text{tr,act}}$ and $P_{\text{tr,nat}}$.

| Case 1 | $r_1 = 10.45$ m | $r_2 = 17.05$ m | $r_3 = 23.55$ m | $r_4 = 30.15$ m | $r_5 = 36.75$ m |
|--------|----------------|----------------|----------------|----------------|----------------|
| $P_{\text{tr,act}}$ | 0.338 | 0.356 | 0.381 | 0.384 | 0.426 |
| $P_{\text{tr,nat}}$ | 0.346 | 0.357 | 0.393 | 0.405 | 0.442 |
| $LEC$ | 2.3 % | 0.3 % | 3.0 % | 5.2 % | 3.6 % |

The thermographic measurement was performed from a measurement distance of 180 m. The results indicate a maximum $LEC$ of 5.2% at the radial section $r_1$, which in the authors’ opinion represents a relatively clean state. On many occasions the authors have measured rotor blades in operation in which the outer third of the rotor blade is practically fully tripped, i.e. no laminar region is present whatsoever in the outer region. This is the case for Fig. 5(b) with a significant level of leading edge contamination in the outer half of the rotor blade. The measurement distance for this measurement was 110 m. The evaluation of the $LEC$ results in a maximum of 90.4% at the radial section $r_4$. Due to the high number of turbulence wedges in the outer region of the rotor blade, a determination of the natural transition position $P_{\text{tr,nat}}$ was not possible. Instead, the individual $P_{\text{tr,nat}}$ of case 1 for the radial sections $r_i$, $i = 2, ..., 5$ are used as a reference. This seems to be applicable since the positions of the natural transition on section $r_1$ are the same in both cases. The results for all five sections are summarised in Tab. 2.

Table 2. Leading edge contamination level ($LEC$) for case 1 at 5 radial positions $r_i$, $i = 1, ..., 5$ with known geometry based on the comparison of the actual and the natural transition positions $P_{\text{tr,act}}$ and $P_{\text{tr,nat}}$.

| Case 1 | $r_1 = 10.45$ m | $r_2 = 17.05$ m | $r_3 = 23.55$ m | $r_4 = 30.15$ m | $r_5 = 36.75$ m |
|--------|----------------|----------------|----------------|----------------|----------------|
| $P_{\text{tr,act}}$ | 0.340 | 0.154 | 0.090 | 0.039 | 0.129 |
| $P_{\text{tr,nat}}$ | 0.340 | 0.357 | 0.393 | 0.405 | 0.442 |
| $LEC$ | 0.0 % | 56.9 % | 76.4 % | 90.4 % | 70.8 % |
Figure 5. Leading edge condition measurements on the suction side of the rotor blade with a rotor radius of 38.5 m in two different conditions. (a) Thermographic measurement results from a working distance of 180 m with an exceptionally clean rotor blade (case 1). (b) Thermographic image of the same rotor blade from a working distance of 110 m with a significant level of leading edge contamination (case 2). The results at the five radial sections $r_i, i = 1, ..., 5$ are summarised for both cases in Tab. 1 and Tab. 2.
3.2. The aerodynamic impact of the leading edge contamination
In addition to the wind tunnel data, the well-known software Xfoil (v6.97) [14] was used to determine the change in aerofoil lift and drag polars due to the presence of leading edge contamination. Two different contamination cases were evaluated corresponding to the two different thermography results as described in section 3.1. For case 1 changes in the transition position on both the suction and pressure side were considered whereas in case 2 only the suction side was considered due to the available data and due to the fact that the pressure side is tripped at 50 %, which reduces the possible impact of a pressure side tripping or contamination. Each aerofoil’s performance was analysed at its operational angle of attack (taken from the BEM results in the constant pitch partial-load operating region) before manually setting a transition location further forward by the amount determined through on-site thermography; this allowed the calculation of a performance delta that could be applied to the aerofoil polars. The performance deltas applied to each aerofoil for each case are shown in Tab. 3 and Tab. 4. In case 1 the performance deltas are very small due to the minimal shift in transition whereas in case 2 the lift loss and drag increase are significant.

Table 3. Case 1 aerofoil performance deltas evaluated with Xfoil.

| Profile | SS LEC | PS LEC | ΔcL | ΔCD |
|---------|--------|--------|-----|-----|
| r1 = 10.45 m | 2.3 % | 0.0 % | -1.0 % | +3.0 % |
| r2 = 17.05 m | 0.3 % | 0.0 % | 0.0 % | 0.0 % |
| r3 = 23.55 m | 3.0 % | 0.4 % | -0.4 % | +4.0 % |
| r4 = 30.15 m | 5.2 % | 3.2 % | -0.2 % | +4.0 % |
| r5 = 36.75 m | 3.6 % | 2.0 % | -0.1 % | +2.0 % |

Table 4. Case 2 aerofoil performance deltas evaluated with Xfoil.

| Profile | SS LEC | PS LEC | ΔcL | ΔCD |
|---------|--------|--------|-----|-----|
| r1 = 10.45 m | 0.0 % | 0.0 % | -0.1 % | +0.2 % |
| r2 = 17.05 m | 56.9 % | 0.0 % | -2.0 % | +45.0 % |
| r3 = 23.55 m | 76.4 % | 0.0 % | -4.0 % | +75.0 % |
| r4 = 30.15 m | 90.4 % | 0.0 % | -9.0 % | +70.0 % |
| r5 = 36.75 m | 70.8 % | 0.0 % | -6.0 % | +45.0 % |

The modified aerofoil polars were used to replace their corresponding clean polars in the BEM simulation, which was carried out using the same global turbine operating parameters as the baseline cases. The AEP results are compared in Tab. 5. The very small amount of leading edge contamination measured in case 1 results in a very small AEP loss of 0.2 % to 0.1 %. It would be difficult to measure an AEP loss of this low magnitude in reality because the AEP delta would be within the uncertainty of the measurement. Case 2 yields a much larger AEP loss of 4.7 % to 2.7 % for the investigated average wind speeds between 6 m/s and 9 m/s due to the greatly increased leading edge contamination that approaches the AEP loss obtained using fully tripped polars. A precipitation-filtered measurement analysis performed in [15] on data over a 4 year period of a megawatt-class wind turbine showed differences in the AEP in the same order of magnitude. The results demonstrate a simple method whereby an estimate of the performance reduction due to the leading edge contamination can be calculated. The results for
Figure 6. \( c_L/c_D \) vs. blade radius \( r \) for the clean and the tripped condition as well as the measured leading edge contamination cases 1 and 2.

both cases demonstrated are between the clean and the tripped condition. Fig. 6 presents the \( c_L/c_D \) vs. blade radius \( r \) curve for the four cases in Tab. 5. It can be seen that both leading edge contamination cases reduce the blade \( c_L/c_D \): case 1 only has a small impact on \( c_L/c_D \) as reflected in the AEP results whereas case 2 reduces \( c_L/c_D \) by similar levels to the leading edge tripped (zig-zag) case.

Table 5. AEP loss for the 3 cases, leading edge contamination case 1, leading edge contamination case 2 and tripped compared to the clean case. The results for the AEP loss are given for average wind speeds of 6 m/s, 7.5 m/s, 8 m/s and 9 m/s.

| Case               | AEP loss at 6 m/s in % | AEP loss at 6 m/s in MWh | AEP loss at 7.5 m/s in % | AEP loss at 7.5 m/s in MWh | AEP loss at 8 m/s in % | AEP loss at 8 m/s in MWh | AEP loss at 9 m/s in % | AEP loss at 9 m/s in MWh |
|--------------------|------------------------|--------------------------|--------------------------|---------------------------|------------------------|--------------------------|------------------------|--------------------------|
| clean              | -                      | -                        | -                        | -                         | -                      | -                        | -                      | -                        |
| case 1             | -0.2                   | -7                       | -0.2                     | -8                        | -0.2                   | -8                       | -0.1                   | -8                       |
| case 2             | -4.7                   | -143                     | -3.6                     | -171                      | -3.3                   | -173                     | -2.7                   | -171                     |
| tripped \( r_3 - r_5 \) | -6.1                  | -186                     | -4.9                     | -235                      | -4.6                   | -242                     | -3.9                   | -245                     |

4. Conclusions and future work

It is standard practice in the industry to use both clean and tripped aerofoil data to analyse two extreme operating conditions. This paper proposes an extension by allowing the impact of more representative real world data to be analysed. Thermographic flow visualisation can be used to obtain a snapshot of the rotor blade’s aerodynamic condition at a given point in time that can be converted to an expected performance loss due to the leading edge contamination. The methods outlined in this paper could be used as the basis for an automated method to assess the need for blade cleaning/repair based on the individual turbine’s economic case.

The leading edge condition of a rotor blade was measured by means of thermographic flow visualisation. A comparison of the natural (clean) transition and the actual transition affected
by surface imperfections due to leading edge erosion or contamination provides a leading edge contamination level \((LEC)\). The contamination level is defined as the difference between the natural and the actual transition position \(P_{tr,act}\) and \(P_{tr,nat}\) normalised to the natural transition position, which serves as a measure for the leading edge contamination. The positions of the actual and the natural laminar-turbulent transition are used as an input for a flow simulation to predict the performance change due to the surface condition at the leading edge. The presented thermographic measurements show a maximum \(LEC\) of 5.2\% for the clean case 1, resulting in a calculated annual energy production (AEP) loss of less than 0.2\% for all investigated wind speeds, and a maximum \(LEC\) of 90.4\% for the heavily contaminated leading edge in case 2, resulting in an AEP loss of 4.7\% to 2.7\% for average wind speeds between 6 m/s and 9 m/s.

It can be seen from the thermographic images that the leading edge contamination does not result in a uniform forward movement of the transition location. While the method described in this work will give a usable estimate of the power curve impact of the leading edge contamination it may be possible to improve the accuracy by combining the field thermographic images with the results of a wind tunnel campaign that investigates the performance impact of different densities of turbulence wedges caused either by roughness increase or leading edge geometry variations on aerofoil performance. The BEM methodology would remain the same, but instead of using \(Xfoil\) in isolation to calculate performance deltas based on bulk transition movements, it could be combined with performance deltas measured in the wind tunnel. It is also important to note that even if thermography were to identify sections of the blade as having a turbulent boundary layer extending from the leading edge, using fully tripped aerofoil data (whether from the wind tunnel or \(Xfoil\)) might not be conservative because the leading edge contamination in some forms has been demonstrated to have a larger impact on aerofoil performance than the industry-standard wind tunnel testing technique of tripping using zig-zag tape [1]; however, it is the authors’ opinion that the use of zig-zag tape provides a convenient, repeatable and representative method of measuring the impact of leading edge contamination on the aerodynamic polars. It is not possible with the current thermography techniques to differentiate between different forms of leading edge contamination with a single measurement, which is another reason why using zig-zag tape data is reasonable - it will have a larger impact on the aerofoil performance than some contamination of the leading edge and a lesser one than others.

Another aspect of future work could be a long-term field measurement campaign that logs the measured seasonal contamination level, and identifies the relations between contamination, weather, and performance data, which would be necessary for a more complete evaluation of the AEP losses.

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