Advanced image processing for turbulence wedge detection in thermographic flow visualization on wind turbines in operation

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Abstract. Environmental conditions like the presence of rainfall or insects can disturb the rotor blade surface of wind turbines in operation, triggering a premature laminar-turbulent flow transition in the boundary layer flow. The local contaminations develop a wedge-shaped surface area of turbulent flow in the area that would otherwise be laminar if the surface would be undisturbed, decreasing the size of the laminar flow regime. This change in the ratio between overall laminar and turbulent flow regime sizes has a negative impact on the aerodynamic performance of the profile, decreasing the efficiency of the wind turbine. While the spatial distribution of the flow regimes can be visualized with thermographic flow visualization, the state-of-the-art image processing method for applications on wind turbines in operation is not robust against localizing the position of the flow transition along these turbulence wedges. Therefore, this work introduces an advancement of the image processing method for localizing the flow transition in thermographic images with a focus on decreasing the localization uncertainty along the turbulence wedges. The state-of-the-art one-dimensional evaluation method is enhanced by a two-dimensional image processing method in order to increase the directional gradients at the turbulence wedges' flanks. Six out of six previously undetected turbulence wedges are successfully detected in a flow visualization image of a rotor blade of a GE 1.5 sl wind turbine in operation. The new approach yields an improved application of the thermographic flow visualization for locating the flow transition and quantifying the reduction of the laminar flow area on disturbed rotor blade surfaces of wind turbines in operation.

1. Introduction
The shape and surface quality of the aerodynamic profiles of rotor blades on wind turbines have a decisive influence on the resulting boundary layer flow and thus a direct influence on the overall lift and drag coefficient. One quantifiable characteristic of the boundary layer is the position of the flow transition between the laminar and turbulent flow regime [1]. The course of the flow transition is parallel to the leading edge of the rotor blade and crosswise to the flow direction and is hereinafter referred to as natural flow transition. Leading edge disturbances of the rotor blade surface on wind turbines during operation can trigger a premature flow transition and create turbulence wedges in areas that would be laminar if the surface would be undisturbed. This reduction of laminar flow and increase of the turbulent flow regime has a negative impact on the aerodynamic drag of the rotor blade and consequently efficiency [2, 3, 4].
In order to quantify the spatial distribution of the flow regimes and the reduction of the laminar flow regime by turbulence wedges due to surface disturbances, a measurement of the boundary layer flow and localization of the laminar-turbulent flow transition is required. The localization of the flow transition and quantification of reduces laminar flow can afterwards be used as an indicator of efficiency loss and yields therefore an important input for maintenance and optimization options. The requirements for the measuring system for use on wind turbines in operation is a planar, contactless and non-invasive method with a high geometrical resolution in order to resolve the local flow phenomena triggered by the surface disturbances.

A measurement method that is able to visualize the boundary layer flow without the requirement of supplements like tufts [5] is the thermographic flow visualization [6, 7]. An initial temperature difference between fluid and surface results in different surface temperatures depending on the flow regimes’ friction correlated heat flux [8]. The thermographic flow visualization is already broadly used in the fields of supersonic [9, 10] and subsonic [11, 12] flow analysis. A common application is the localization of the laminar turbulent flow transition [13, 14], the identification of laminar separation bubbles [15, 16] and turbulent separation [17, 18]. However, most of these applications are wind tunnel experiments. Automatic evaluation methods were introduced by Crawford et al. [19] and Joseph et al. [20]. A transfer from the laboratory environment to field measurements were successfully conducted for aircraft wings [21, 22] and rotating helicopter rotor blades [23, 24]. A transfer of the thermographic measurement principle onto rotor blade of wind turbines in operation was made by Dollinger et al. using a one-dimensional temperature gradient evaluation in the direction of the flow [7, 4] and builds the base for this work.

The image evaluation method by Dollinger et al. is optimized for localizing the natural flow transition on an undisturbed surface. Because of the diagonal course of the flow transition at the flanks of the turbulence wedges, the one-dimensional image processing method in flow direction has a high localization uncertainty in these areas, resulting in undetected turbulence wedges. Therefore an advancement of the method is introduced that can minimize the systematic measurement error of the laminar-turbulent flow transition in the areas of turbulence wedges by extending the one-dimensional evaluation to a two-dimensional image processing. A comparison between the position of the natural flow transition on an undisturbed rotor blade surface and the position of the actual occurring flow transition enables the possibility to quantify the amount of flow-influencing surface disturbances. Because of the direct correlation between the apparent flow regimes in the boundary layer and the lift and drag coefficients of the aerodynamic profile, this quantification has direct influence on the assessment of the efficiency of the wind turbine [4]. As a result, more turbulence wedges which were previously undetected can be detected and their influence on the reduction of laminar flow regime can be quantified.

In Sect. 2 the methodology of the thermographic flow visualization as well as the current image processing method for localizing the flow transition is introduced. Afterwards an explanation of the evaluation’s limitation concerning the detection of turbulence wedges is given and the new advanced two-dimensional image processing is introduced. In Sect. 3 the result of the flow transition localization for a General Electric wind turbine type 1.5 sl is presented in order to show the improvement in the turbulence wedge detection. The article finishes with a conclusion and outlook in Sect. 4.

2. Methodology

Fig. 1 shows an image of a thermographic flow visualization measurement on a General Electric 1.5 sl wind turbine in operation. The rotor blade is in a downwards movement, resulting in a relative upwards flow direction. The background, the laminar (brighter) and the turbulent (darker) flow regime can be distinguished by the different temperature levels detected by the IR-camera. The localization of the regions’ borders is achieved by evaluating the temperature
gradients from one region to the other. While the contrast between the background and the surface is high enough to robustly localize the leading (LE) and trailing edge (TE) of the visual rotor blade surface, the laminar-turbulent flow transition is more difficult to be localized due to varying temperature gradients between the two flow regimes.

Figure 1. Thermographic image of a wind turbine rotor blade in operation. A clearly visual difference in temperature between the background, as well as the laminar and turbulent flow regime on the blade surface, is notable. Dark wedges in the bright area are clearly visible turbulence wedges in the laminar flow regime due to surface disturbances.

The straight dividing line between the turbulent and laminar flow regime is marked with a dashed line and represents the position of the natural flow transition if the blade surface would be undisturbed. Due to the existence of multiple surface disturbances triggering premature flow transitions, 11 wedge-shaped areas of turbulent flow can be noted within the area of the otherwise laminar flow regime. The selected image has wedges of varying size and contrast in order to evaluate the robustness of the introduced flow transition localization. These turbulence wedges reduce the overall size of the laminar flow regime (bright surface area) and increase the size of the turbulent flow regime (dark surface area), resulting in an increase of the aerodynamic drag of the rotor blade. Hence a metrological assessment of the areas of turbulent flow regime due to a premature flow transition as a quality criterion for the aerodynamic evaluation of the rotor blade is required.

2.1. state-of-the-art (one-dimensional approach)
Due to the line-shaped course of the natural flow transition on an undisturbed rotor blade surface (cf. Fig. 1 dashed line), the direction of the standard one-dimensional image evaluation is conducted line-shaped and parallel to the flow direction. The position of the flow transition is determined by locating the maximum temperature gradient in each image column between the leading and trailing edge of the rotor blade surface.

Figure 2. Thermographic image from Figure 1 with localized actual flow transition by the one-dimensional image evaluation process. It can be noted, that the course of the transition along multiple turbulence wedges was not detected successfully.
Fig. 2 shows the localized actual flow transition course along the rotor blade in the same thermographic image from Fig. 1. Along the flanks of turbulence wedges, the flow transition is diagonal and consequently not perpendicular to the columnar evaluation lines. Due to this inclined alignment, the temperature step between the laminar and turbulent flow regime in the image columns with a wedge flank is stretched, resulting in a smaller temperature gradient in the region of the transition. The small gradient in the evaluation line therefore increases the localization uncertainty of the flow transition point for the respective evaluation. A secondary influence on the localization is the temperature field of lower surface temperature near the leading edge. Evaluation lines in the image sections around the tips of the turbulence wedges show a nearly constant temperature profile from leading to trailing edge, making it impossible to localize the flow transition point by evaluating the temperature gradient. From all 11 visible turbulence wedges only five get detected, while only one wedge (no. 1) can be considered as detected successfully. Therefore the state-of-the-art one-dimensional evaluation approach for localizing the flow transition is insufficient for the existence of turbulence wedges in the thermographic image and the subsequent evaluation of the laminar flow reduction.

2.2. Advanced evaluation (two-dimensional image processing)

In order to maximize the sensitivity of the flow transition localization, especially in the areas of the turbulence wedges, this research work aims to advance the current one-dimensional evaluation by a multi-dimensional approach in order to maximize the temperature gradients of the line-wise evaluations of the temperature gradient in each evaluation step by aligning the evaluation line perpendicular to the flow transition course. Afterwards the more precisely acquired position of the flow transition is used to calculate different figure of merits for quantifying the influence of the surface contamination on the boundary layer flow.

A manual evaluation by the author yields an average angle between the y-axis and the turbulence wedges’ flanks of \( \alpha_{\text{wedge}} = 6^\circ \). A rotation of the image by \( \alpha_{\text{rotate},1} = 84^\circ \), \( \alpha_{\text{rotate},2} = 0^\circ \) and \( \alpha_{\text{rotate},3} = 94^\circ \) aligns the flanks of the turbulence wedges nearly parallel to the \( x' \)-axis in the rotated image (cf. Fig. 3). A subsequent column by column evaluation (black line) parallel to the \( y' \)-axis aligns perpendicular to the turbulence wedges’ flanks. This perpendicular alignment results in sharper temperature steps between the flow regimes at the positions of the flow transitions, allowing a flow transition localization with reduced uncertainty by evaluation the therefore increased temperature gradient.

Because of the new orientation, each column in the rotated image may inherit multiple flow transitions. In order cope with these multiple occurrences, the temperature gradient evaluation of each column-temperature profile \( (T)_j \), with \( j = 1, ..., J \) columns is conducted multiple times using different thresholds \( dT_{\text{thresh}} \). The position of the gradients higher than the respective threshold are saved as points of interest (POI). By using descending values for the threshold, the respective \( dT_{\text{thresh}} \) can be used as a weighting factor \( w \) for each POI. Consequently, image points detected with a high threshold get a high weighting factor and vice versa. Fig. 3 shows two examples of the same column evaluated in the rotated image by using two different gradient thresholds \( dT_{\text{low}} \) and \( dT_{\text{high}} \).

After the multiple image rotations by all angles \( \alpha_{\text{rotate}} \) and subsequent temperature profile evaluations, all POI of all evaluation steps are bundled as one point cloud of weighted POI in the un-rotated thermographic image. Since the flow direction in the un-rotated thermographic image is vertical, per definition each image column can have only one pixel representing the centre of the actual flow transition. The coordinate of the flow transition point in each column is therefore calculated by

\[
y_{tr,j} = \frac{\sum_j y_{poi,j} \cdot w_j^2}{\sum_j w_j^2}
\]
where \( y_{poi,j} \) are the \( y \)-coordinates and \( w_j \) the corresponding weighting factors of the points of interest in the respective column \( j = 1, \ldots, J \).

### 2.3. Quantification of the laminar flow reduction

Using a fitting approach robust towards outliers, a regression of the transition points \( y_{tr,j} \) for all \( j = 1, \ldots, J \) (cf. Sect. 2.2) results in a line, representing the course of the natural flow transition, as transition points along the turbulence wedges are excluded. The calculation of the distance between the natural transition \( y_{tr,nat} \) and the actual transition \( y_{tr,act} \) in each column, normalized to the distance between leading edge \( y_{LE} \) and the natural transition yields the parameter

\[
d_{wedge} = \frac{|y_{tr,act} - y_{tr,nat}|}{|y_{LE} - y_{tr,nat}|}. \tag{2}
\]

The parameter \( d_{wedge} \) represents the relative size of the laminar surface area reduced by turbulent flow. The quantification of the LFR (laminar flow reduction) of \( J \) pixel columns is subsequently defined by the average of each column’s \( d_{wedge,j} \):

\[
LFR_{mean} = \frac{1}{J} \sum_{j=1}^{J} d_{wedge,j}. \tag{3}
\]

### 3. Results

Fig. 4 shows one section of the thermographic image in Fig. 1 with three turbulence wedges. The red and green dots are the image processing results of the one- and two-dimensional temperature gradient evaluation, respectively. The one-dimensional approach only detects one wedge with high uncertainty of the transition localization in each image column in the area of the wedge. The two-dimensional image processing successfully detected the turbulence wedges’ flanks along all three wedges with only minor outliers. This proofs the advancement of the two-dimensional image processing in order to locate the flow transition along the turbulence wedges.

Fig. 5 shows another image section with the occurrence of a turbulence wedge with low contrast as well as two turbulence wedges close to each other. Both types of wedges proof to
Figure 4. Example of the improved turbulence wedge detection. Red squares: Result of the one-dimensional evaluation. Green dots: Result of the two-dimensional image processing. The flow transition along the turbulence wedges was successfully localized with the new approach.

Figure 5. Example of the improved turbulence wedge detection. Red squares: Result of the one-dimensional evaluation. Green dots: Result of the two-dimensional image processing. The flow transition along the closely positioned turbulence wedges was not entirely successful by neither approach.

be the limit of the two-dimensional image processing. The localization of the right-hand side’s flank of the low-contrast wedge has a high uncertainty due to no sharp temperature step. The

Figure 6. Evaluated thermographic image of Fig. 1 for comparison between the one-dimensional and two-dimensional image processing for localizing the actual flow transition. Six turbulence wedges undetected by the old approach are successfully detected by the new one. The transition along all previously detected wedges is localized with a smaller deviation. For comparison the manually evaluated transition is shown with a black line.
combination of a small laminar flow area between the wedges and a necessary smoothing of the image also results in a low temperature gradient that increases the flow transition localization uncertainty. The right hand side of the left, small turbulence wedge is not detected sufficiently. Both type of turbulence wedges are not detected by the one-dimensional evaluation localization at all, hence the two-dimensional image processing still yields an improvement. A look at the overall thermographic image in Fig. 6 enables an obvious evaluation of the introduced two-dimensional image processing compared to the one-dimensional one. For comparison, a manual evaluation of the visible transition course was carried out by the researcher and depicted with a black line. The two-dimensional gradient evaluation (green line) successfully detected all 11 turbulence wedges, while the one-dimensional approach only detected five with only one successful detection. The uncertainty of the flow transition localization at low-contrast wedges (no. 2, 7, 8) is higher, as the wedges’ tips are not included. This is due to the weighted calculation of the final transition point by evaluating the POI in each column and therefore yields the task of further improvement for successfully detecting the wedges’ tips. The laminar flow reduction defined in Eq. 3 for the depicted surface area in Fig. 6 yields a \( LFR_{2D} = 21.43\% \) for the two-dimensional image processing. The size of the laminar flow regime is therefore reduced by approx. 21%. The LFR calculated based on the manual evaluation is \( LFR_{\text{manual}} = 26.42\% \) and \( LFR_{1D} = 7.48\% \) for the 1D gradient evaluation. Hence the error of the calculated laminar flow reduction percentage is reduced from approx. 19 % to 5 %.

4. Conclusion
In order to improve the localization of the laminar-turbulent flow transition along turbulence wedges in thermographic images for flow visualization, the existing one-dimensional image evaluation method is enhanced for reducing the localization uncertainty. The two-dimensional image processing method is able to reduce the systematic deviation of the localized and true position of the flow transition. The improved localization was shown at an sample thermographic image with 11 turbulence wedges. While multiple single turbulence wedges which were previously undetected were localized successfully by the new approach, a limitation of the wedge detection in areas of closely positioned wedges and wedges with low contrast remains as well as a lower limit for the minimum contrast to noise ratio of the turbulence wedges compared to it’s surrounding area. This improvement enables a more accurate quantification of the laminar flow reduction based on rotor blade surface disturbances, its influence on the flow distribution and subsequently the impact on the wind turbines efficiency.

Future work needs to address a further advancement of the image processing method to improve the robustness of detecting varying turbulence wedges concerning their form, size and contrast as well as a group of closely positioned wedges. The quantification of the reduced laminar flow regime can be used in simulations for the lift and drag coefficient for estimating the annual power loss due to the surface disturbances. These quantifications can be used directly for maintenance decisions and yield information for the development of new rotor blades.

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