

High-speed measurements of different laminar-turbulent transition phenomena on rotor blades by means of infrared thermography and stereoscopic PIV

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Abstract Surface defects as well as uncontrolled boundary layer (BL) transition on rotor blades of wind energy turbines can cause significant power loss and unfavorable dynamic loads. Consequently, there is a strong demand for a remotely working and easily applicable condition monitoring method of rotor blades which is able to visualize the actual state of the flow. As infrared thermography (IRT) can meet these requirements, it is used to image the formation of turbulent wedges induced by different turbulators as well as the motion of free BL transition on a DU 91-W2-250 profile. Initially, a validation of Particle Image Velocimetry and IRT is performed in a simplified setup with a BL on a flat plate. Both methods show very good agreement which enables IRT to represent the actual flow properties in the BL appropriately with minimal effort. With respect to wind turbines, differences in appearance of turbulent wedges enable conclusions about the kind of turbulator based on the thermogram. Additionally, lift measurements show an inferior performance of an airfoil modified with turbulators regarding lift and dynamic loads. In order to capture the dynamics of laminar-turbulent transition on an airfoil conventional IRT is improved. Using aluminum as an airfoil material with a low thermal response time, it can be shown that this new approach gives sufficiently high contrast to capture a highly unsteady BL without any elaborate temperature contrast enhancement. In this way, the fluctuation of the laminar-turbulent transition region on an airfoil is characterized and conclusions towards unfavorable dynamic loads are drawn.

Keywords: laminar-turbulent transition; turbulent boundary layer; turbulent wedges; high-speed infrared thermography; high-speed stereoscopic PIV; wind energy; condition monitoring; aerodynamics

1 Introduction

Wind turbines operate under highly unsteady and partly harsh flow conditions in the atmospheric boundary layer on- and offshore. Emerging surface defects on rotor blades as well as uncontrolled boundary layer (BL) transition and stall arising from constantly changing ambient flow conditions can cause significant power loss and unfavorable dynamic loads. Consequently, there is a strong demand for a remotely working and easily applicable condition monitoring method of rotor blades, which is able to visualize the actual state of the flow on-site. Infrared thermography (IRT) can meet these requirements as it is a non-intrusive imaging technique representing the surface flow by resultant temperature differences. These appear due to a flow specific heat transfer between the rotor blade and the free flow that occurs significantly when temperatures of surface and flow are different. Depending on whether the flow is warmer or colder than the rotor blade, turbulent regions appear warmer/colder on the surface as they apply a higher convective heating/cooling. In the most general sense, every flow feature implies a certain convective cooling or heating, hence being potentially recognizable in a thermogram. For further details about the physical background see [1].

A typical thermogram of a moving rotor blade after just a couple of years in operation is depicted in figure 1 (color coded in greyscale, the darker the colder). The thermal pattern clearly shows turbulent wedges generated by surface defects, originating at the leading edge and merging into the natural laminar-turbulent transition hereafter referred to as transition. In this case, turbulent regions appear colder as the rotor blade is warmed up by the morning sun and the air is still cold from the night.

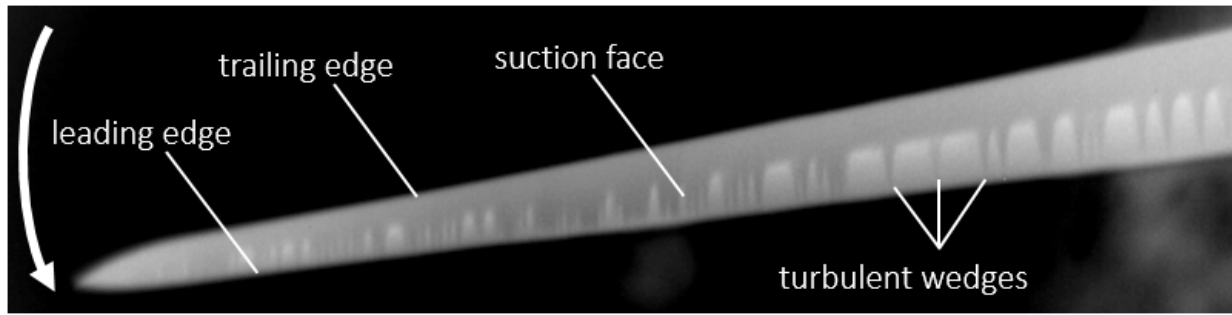


Fig. 1 Thermogram of a rotor blade's suction face on an operating wind turbine (movement is downwards): free laminar-turbulent boundary layer transition and turbulent wedges generated by surface defects appear darker.

Certainly, not every turbulent wedge corresponds to a severe defect, but figure 1 draws a vivid picture of an average rotor blade's condition. As surface defects are to be avoided for economic reasons, this experimental study aims at establishing IRT as a remotely working condition monitoring method that is capable of concluding the kind of defect and its impact on the rotor blade's performance just from the flow formation mapped by the thermogram. As a further aim, an investigation of unsteady transition phenomena at rotor blades of operating wind energy turbines shall be enabled employing IRT that has not been performed before. In this way, knowledge about the dependence of transition on temporal effects such as gusts can be gained and implications such as resultant unfavorable dynamic loads can be derived.

In order to achieve these objectives, the present study is structured in three chapters with some concluding remarks in the end. Chapter 2 covers the flow topology in the wake of representative surface defects in a simplified setup on a flat plate. With respect to a thermogram, the corresponding thermal footprint is determined for each defect. This allows distinguishing the kind of defect by means of the thermogram only. In chapter 3, the formation of turbulent wedges induced by surface defects is investigated on airfoils. This consideration provides a conclusion to what extent thermal features observed on a flat plate can be identified on an airfoil as well. Furthermore, the effect of defects on the performance of an airfoil is assessed by means of lift measurements. Finally, the so far steady and induced transition is extended in chapter 4 to the dynamics of free transition on an airfoil employing IRT. This examination proves the capability of IRT as a simple technique in a standard experimental setup to localize transition temporally resolved. As fluctuations of the transition area are usually caused by unsteady inflow, their occurrence suggest dynamic loads that cause fatigue on wind turbines on-site.

2 Characteristics of turbulent wedges on a flat plate

Boundary layer transition is a highly unsteady process which emerges stochastically over a certain region on rotor blades. In order to investigate this complex and delicate flow topology appropriately, it is crucial to use spatially and temporally highly resolving as well as non-intrusive methods. Therefore, high-speed stereoscopic particle image velocimetry (HSPIV) and IRT in a temporally highly resolving way are used in this experimental study. In a first step the fundamental link between defects, the resultant flow topology and corresponding thermal features is to be found. For this reason, turbulent wedges are investigated as temporal mean fields in a simplified setup on a flat plate with generic defects, of which a schematic representation is given in figure 2. In the further course of the present study advantage is taken from the temporal resolution of the two methods.

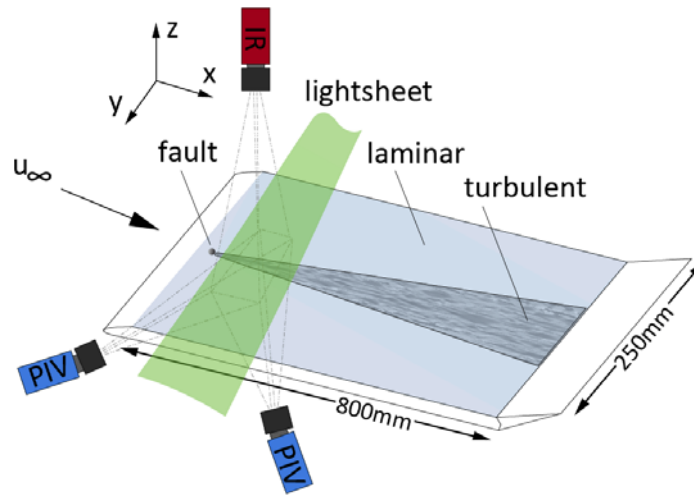


Fig. 2 Experimental setup for HSPIV and IRT measurements of a turbulent wedge emerging on a flat plate downstream of defect/turbulator.

The used HSPIV configuration consists of two Phantom Miro M320S high-speed cameras and a Litron LDY300 laser. This enables HSPIV measurements with a recording frequency of 695 velocity fields per second at full resolution of $1920 \times 1200 \text{ px}^2$. The light sheet is adjusted parallel to the surface in a distance $z/\delta = 50\%$ where δ denotes the 99% BL thickness of the laminar BL and z the distance to the surface. In this way, a sufficient accuracy (stereo residue $< 0.5 \text{ px}$) and velocity contrast between the laminar BL and the wake of the defect is obtained. The utilized infrared camera IRCAM Equus 327k M with a resolution of $640 \times 512 \text{ px}^2$ is adjusted perpendicular to the surface. Since the results presented in this chapter are steady state only a high integration time of 2ms along with a thermal resolution of $\Delta T = 15 \text{ mK}$ yields low-noise and detailed thermograms. Both measurement techniques cover congruent regions of interest of approximately $\Delta x \times \Delta y = 20 \times 70 \text{ mm}^2$ in the wake of the defect where x and y are denoted according to figure 2. Due to very complex damage patterns on real rotor blades a generic defect consisting of a hemisphere with a diameter $d = 3.5 \text{ mm}$ serves as a turbulator located at a distance of $\Delta x = 100 \text{ mm}$ from the flat plate's leading edge. The black PVC plate (size: $800 \times 250 \text{ mm}^2$) is provided with a high precision hyperelliptic leading edge keeping the BL attached and laminar [2]. Obviously, induced transition is strongly dependent on ambient flow conditions such as Reynolds number or free stream properties. Minimizing the impact of the latter, the experiments are performed in a wind tunnel (inlet: $250 \times 250 \text{ mm}^2$, length: 2000 mm , closed test section) with a low turbulence intensity $Ti < 0.4\%$. An increasing Reynolds number with respect to the turbulator's height $Re_{d/2} = u_\infty d / \nu$, where u_∞ denotes the free stream velocity and ν the kinematic viscosity, corresponds to a stronger destabilization of the BL and hence a more severe defect. Consequently, the effective size of the turbulator is modified by varying $u_\infty \in [7; 17] \text{ m/s}$ respectively $Re_{d/2} \in [700; 1750]$.

Initially, the formation of turbulent wedges is analyzed by means of HSPIV. Increasing $Re_{d/2}$ from 700 to 1750, the temporal mean over 1800 instantaneous velocity fields is given in figures 3–5 for three characteristic $Re_{d/2}$. The flow's velocity magnitude normalized by u_∞ is color coded and the position in x and y direction refers to the turbulator's location defining the origin.

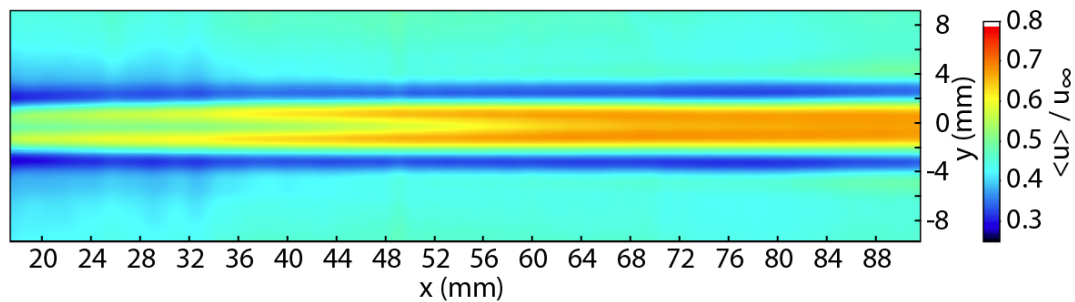


Fig. 3 Averaged HSPIV measurement of a turbulent wedge on a flat plate downstream of turbulator. Turbulator d at $(x; y) = (0; 0)$, $Re_{d/2} = 700$, velocity magnitude u normalized by free stream velocity u_∞ , light sheet parallel to surface.

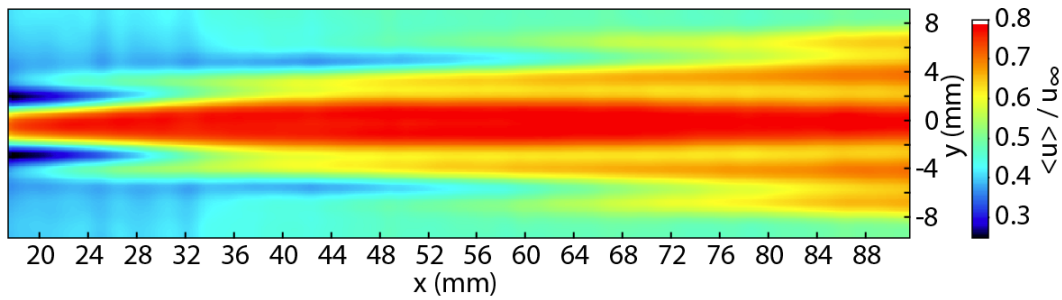


Fig. 4 Averaged HSPIV measurement of a turbulent wedge on a flat plate downstream of turbulator. Turbulator d at $(x; y)=(0; 0)$, $Re_{d/2}=1150$, velocity magnitude u normalized by free stream velocity u_∞ , light sheet parallel to surface.

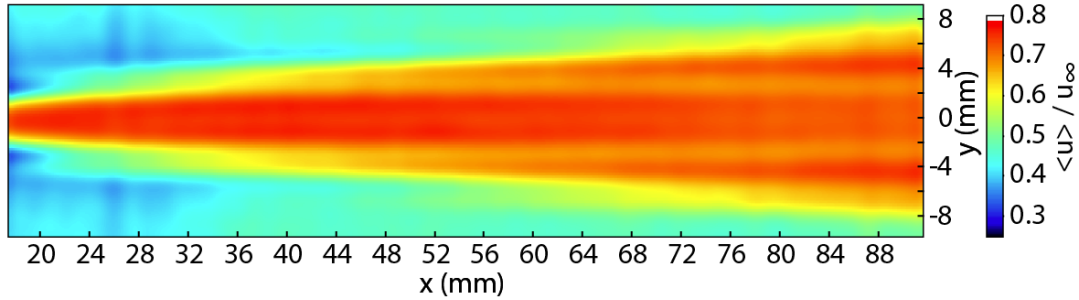


Fig. 5 Averaged HSPIV measurement of a turbulent wedge on a flat plate downstream of turbulator. Turbulator d at $(x; y)=(0; 0)$, $Re_{d/2}=1750$, velocity magnitude u normalized by free stream velocity u_∞ , light sheet parallel to surface.

As these measurements are taken in a distance $z/\delta=50\%$ from the flat plate, a different mean velocity $\langle u \rangle$ than $\langle u \rangle / u_\infty = 50\%$ implies a turbulent mixing of high momentum flow from the free stream in case of $\langle u \rangle / u_\infty > 50\%$ and a turbulent mixing of low momentum flow from the BL closer to the wall in case of $\langle u \rangle / u_\infty < 50\%$. Therefore, regions of relatively higher/lower mean velocity can be associated with vortices or coherent structures. Consequently, the turbulator's wake, in figure 3, reveals a particular flow pattern for a low Reynolds number. Investigating the flow topology around tall obstacles, the appearance of vortex shedding from top of the obstacle, accompanied by horse shoe vortices winding around the obstacle, separating and propagating downstream is known, e. g. according to [3]. As seen in the mean velocity field of figure 3, the four horizontal lines suggest stable remains of two counterrotating horse shoe vortices each consisting of one pair of velocity deficit and overshoot. These vortices are much localized without spreading. In terms of surface defects, a minor defect forms a premature turbulent wedge in its wake. Increasing Reynolds number continuously reveals a characteristic change of the wedge's shape at $Re_{d/2} \approx 1150$ (see figure 4). Suddenly, perturbations arising from the turbulator start to spread in a temporally coupled manner symmetrically around $y=0\text{mm}$ which is observed in instantaneous velocity fields. Obviously, the BL becomes more perceptive for weak perturbations forming a ragged contoured wedge in the mean velocity field. Continuing the argumentation of horse shoe vortices, the two vortices from the turbulator induce another counterrotating vortex each. Propagating downstream this cascade proceeds. Further increasing Reynolds number to $Re_{d/2}=1750$ (see figure 5), perturbations instantaneously spread out and form a smoothly shaped turbulent wedge in the mean velocity field. However, coherent structures still occur within the wedge.

Summarizing the findings of the HSPIV investigation, basically three different flow regimes can be identified for different Reynolds numbers. According to the flow's stability, we call these regimes subcritical, critical and supercritical. The corresponding Reynolds numbers are denoted as Re_{sub} , Re_{crit} and Re_{sup} . In respective of surface defects, the severity of a defect can be distinguished by means of its velocity field. This velocity field cannot be measured easily on turning rotor blades of wind turbines. Following the targeted objective, as a next step the thermal pattern of subcritical, critical and supercritical turbulent wedges is to be recorded by IRT. Thereby the extent to which actual flow properties correspond to thermal features can be determined and the capability of IRT distinguishing defects by means of the thermogram will be assessed.

As mentioned in the introduction, temperature differences δT between the surface and the flow are used in this experimental setup revealing a thermographic pattern that maps the flow features. This method can be

called ‘temperature steps’ [4] in this case exploiting a δT emerging from the wind tunnel warmed up by its fan and the cooler laboratory without any elaborative heating/cooling applied on the flat plate. Thermal contrast of turbulent regions remains as long as the PVC plate’s heat capacity and internal equalization by heat conduction are appropriate. As PVC is a highly insulating material the latter is very low potentially revealing very detailed flow features. A thermogram (actually two spatially shifted and stitched thermograms) of $Re=Re_{crit}$ is presented in the background of figure 6 overlaid by an extract of the corresponding HSPIV velocity field. The color coding for the velocity is the same as in figures 3–5. The temperature is depicted in false colors and color coded in arbitrary units to match the color range of the velocity field allowing easier comparison.

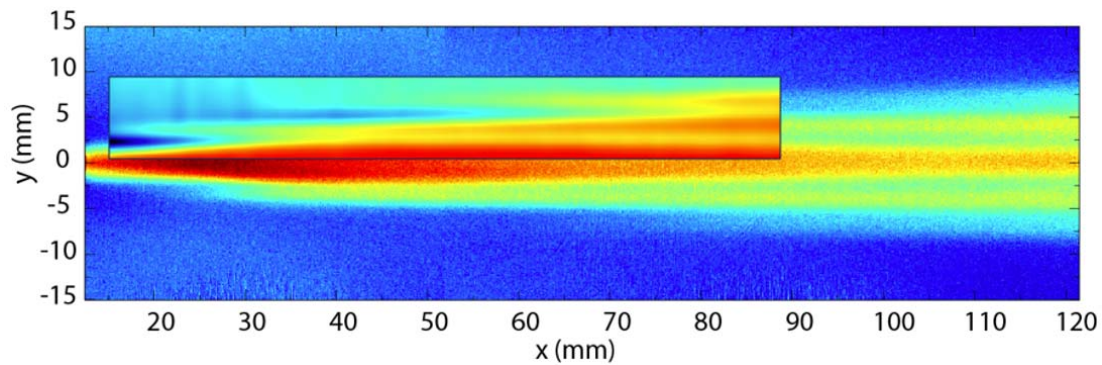


Fig. 6 Comparison of averaged HSPIV (foreground) and IRT (background, false colours) measurements of a turbulent wedge on a flat plate downstream of turbulator d located at $(x, y)=(0; 0)$ for $Re_d=1150$, colour coded in arbitrary units.

Both measurement methods show very good agreement. Every flow feature in the velocity distribution coincides with a counterpart in the thermogram. These findings hold true for the remaining Reynolds numbers Re_{sub} and Re_{sup} . This implies that any particular flow phenomenon in the vicinity of the surface can be potentially mapped in a thermogram. As a result, IRT is capable of representing the actual flow properties in the BL appropriately with minimal experimental effort as well as distinguishing the severity of a defect by means of the thermogram on a flat plate. However, this might be a consequence of the flat plate made of insulating PVC material that suppresses heat conduction transversal to the surface and evokes well defined thermal features within the wedge. Proving this conclusion wrong there is a need of evaluating the extent to which different turbulent wedges are mapped on an airfoil made of a different material. This aspect is treated in the following chapter 3 along with an assessment how relevant surface defects are in an aerodynamic sense.

3 Characteristics of turbulent wedges on airfoils

Usually test objects made of insulating materials are recommended for an IRT investigation [4]. However, aluminum is not considered to be suitable because of its high thermal conductivity blurring any thermal contrast by internal equalization. With respect to airfoils, covering an aluminum airfoil with a thin black PVC foil solves this issue by inhibiting heat conduction transversal to the surface [5]. Thus, sharp thermal imaging with sufficient heat capacity to maintain temperature differences occurring due to the flow is provided. Additionally, the airfoil’s geometry is negligibly changed and thermal reflections are minimized besides a maximized emissivity what is crucial for IRT. This method is very practical as high precision airfoils in wind tunnel tests are often made of aluminum. So is the DU 91-W2-250 wind profile which is under investigation in the following experiment shown in figure 7. In part one of this experiment, the wake of three different turbulators attached to the airfoil close to the leading edge is mapped employing IRT. The extent of thermal details revealed within the wedges allows a comparison to the results of chapter 2. In part two, the performance of the profile modified with a set of five turbulators is determined by means of lift measurements. This yields a measure for the aerodynamic and economic relevance of defects on wind turbine blades on-site.

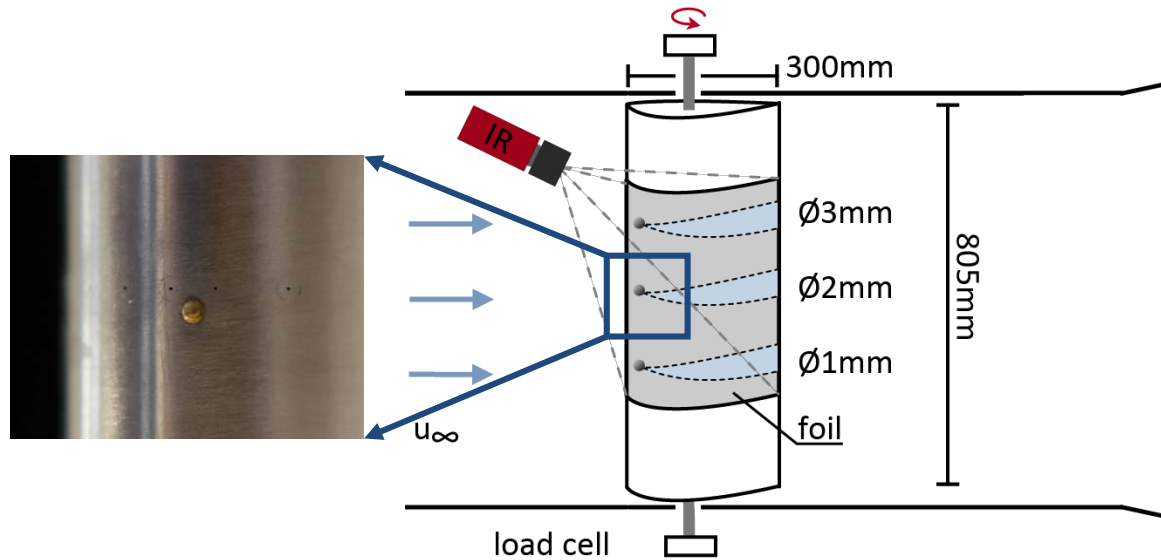


Fig. 7 Experimental setup for lift and IRT measurements of DU 91-W2-250 airfoil modified with turbulators.

For thermal imaging an IRCAM Geminis 327k ML pro with a spatial resolution of $640 \times 512 \text{ px}^2$ and thermal resolution of $\Delta T = 15 \text{ mK}$ is used allowing localization of even small temperature differences. In order to image the turbulent wedges on the curved surface with minor optical distortion, the infrared camera is adjusted perpendicular to the plane that is held by the airfoil's chord length C and span S at zero angle of attack (AoA) α . The airfoil (dimensions: $S \times C = 805 \times 300 \text{ mm}^2$) is mounted at the quarter-chord point on an axis that is turned by a stepper motor setting α precisely. Rather than quantifying the link between thermal and flow features based on Reynolds number under strictly known ambient conditions as performed in a smaller wind tunnel described in chapter 2, part one of this experiment focuses on a qualitative depiction of turbulent wedges. Therefore, this wind tunnel is operated in a half-open setup without infrared absorbing walls or windows at the airfoil's pressure and suction side providing an unobstructed view on the airfoil. Nevertheless, the flow quality $T_i < 0.3\%$ is preserved in center of the test section (inlet: $805 \times 1000 \text{ mm}^2$, length: 2000 mm) enabling investigations on transition phenomena. In this setup, free stream velocities of $u_\infty \in [0; 30] \text{ m/s}$ give Reynolds numbers up to $Re_C = 600.000$ with respect to the chord length. Defects on rotor blades usually occur on the mainly lift generating suction side in distances x from the leading edge $x/C < 13\%$ over the whole spanwise direction y and less frequent towards the trailing edge [6]. Therefore, three hemispherical turbulators (see figure 7 left) of different diameters $d = 1, 2, 3 \text{ mm}$ are attached to the suction side at the position $x/C = 9\%$ displaced in spanwise direction. The camera's field of view covers the three emerging turbulent wedges over the complete chord length enabled by applying a matte black PVC foil $< 100 \mu\text{m}$ underneath the turbulators on the surface of the airfoil due to reasons mentioned above. In figure 7, the sketched load cells are required for the second part of this experiment and are described in the course of this chapter further below.

In analogy to the approach in chapter 2, the method of temperature steps is applied using temperature differences between the up to 2°C cooled wind tunnel flow and the ambient air to image thermal flow features. The resultant thermogram of three turbulent wedges generated by turbulators $d = 1, 2, 3 \text{ mm}$ (from bottom to top) on the DU 91-W2-250 profile is presented in figure 8 for $Re_C = 300.000$.

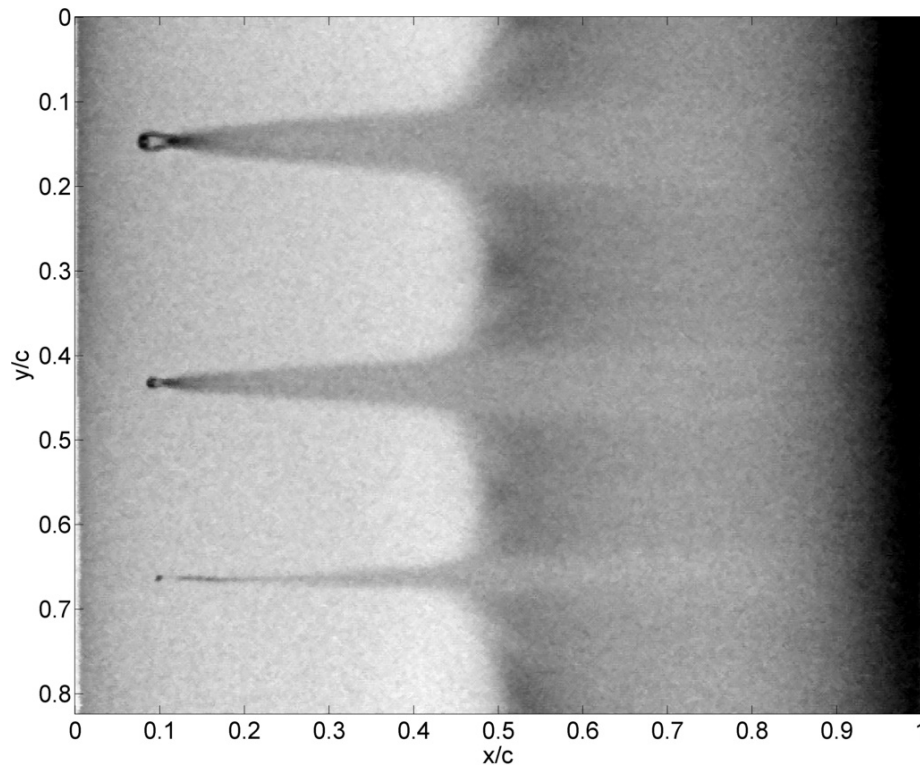


Fig 8 Thermogram of turbulent wedges generated by three hemispherical turbulators of diameter $d=1, 2, 3\text{mm}$ (from bottom to top) on DU 91-W2-250 profile located at $x/C=9\%$ and displaced by $\Delta y/C=50\%$ for $Re_c=300.000$. Depiction in false colours and colour coded in arbitrary units.

As an initial impression, the allegedly suboptimal airfoil material aluminum yields distinct contrast with a lot of thermal features visible. The free transition at $x/C \approx 50\%$ and three turbulent wedges are clearly distinguishable. In this case, different stages of defects are realized by a constant free stream velocity with varying turbulator heights $d/2$ resulting in different Reynolds numbers $Re_{d/2}$, in particular Re_{sub} , Re_{crit} and Re_{sup} . As the smallest one, the bottom turbulator induces quite stable flow features in its near wake forming a nearly straight line. In comparison to figure 3, this appears to be a subcritical turbulent wedge. Obviously, the thermogram shows only one straight line instead of four corresponding to a pair of counterrotating horse shoe vortices. Hence, the thermogram suffers from spatial resolution. However, the subcritical turbulent wedge can still be clearly determined on the aluminum airfoil. A little bit further downstream, the wake of the small turbulator $d=1\text{mm}$ destabilizes and spreads out at $x/C \approx 25\%$. Initially subcritical, the turbulent wedge evolves to a critical one due to effectively increasing Re by a longer path length. Even without resolving the characteristic ragged contoured wedge in details (see figure 4) the critical behavior can be identified. Considering the mapped flow induced by major turbulators in the middle and top of figure 8, two supercritical turbulent wedges appear to be formed. Referring to the explanation in chapter 2, perturbations instantaneously spread out and form a smoothly shaped turbulent wedge. Nevertheless, both supercritical wedges reveal differences in their origin and propagation width. Beyond the three categories of subcritical, critical and supercritical wedges, this enables a further distinction of defect's relevance by means of the thermogram.

These findings represent a key result on the way to achieve the first main objective of the present study. So far, IRT is capable of capturing main characteristics for distinguishing different stages of turbulent wedges that correspond to certain defect severities on flat plates as well as on airfoils. Finalizing the first objective, the impact of severe defects on rotor blade's performance needs to be quantified. For this reason, the setup depicted in figure 7 needs to be slightly modified. According to that, the PVC foil is removed and five equally spaced $\Delta y/C=50\%$ turbulators $d=2\text{mm}$ are applied on the airfoil at $x/C=1\%$. These are considered as a severe defects, whose impact on the DU 91-W2-250 profile's performance is quantified by measuring the lift forces for different AoA. The lift force is obtained by two load cells connected to the airfoil's mounting axis and decoupled from the possibly vibrating wind tunnel. Additionally, the measurements are performed at

$Re_c=1.000.000$ in a completely closed test section avoiding interferences of the flow around the airfoil and the laboratory. In this configuration, lift forces F_L can be measured with an accuracy of $\Delta F/F_{max}<1\%$ at a temporal resolution of $f_s=1\text{kHz}$ where max refers to the maximum load and f_s is the sampling frequency. Figure 9 shows the mean lift forces for different AoA including the corresponding force fluctuations in terms of standard deviation for an airfoil with (denoted as: modified) and without turbulators (denoted as: clean) applied.

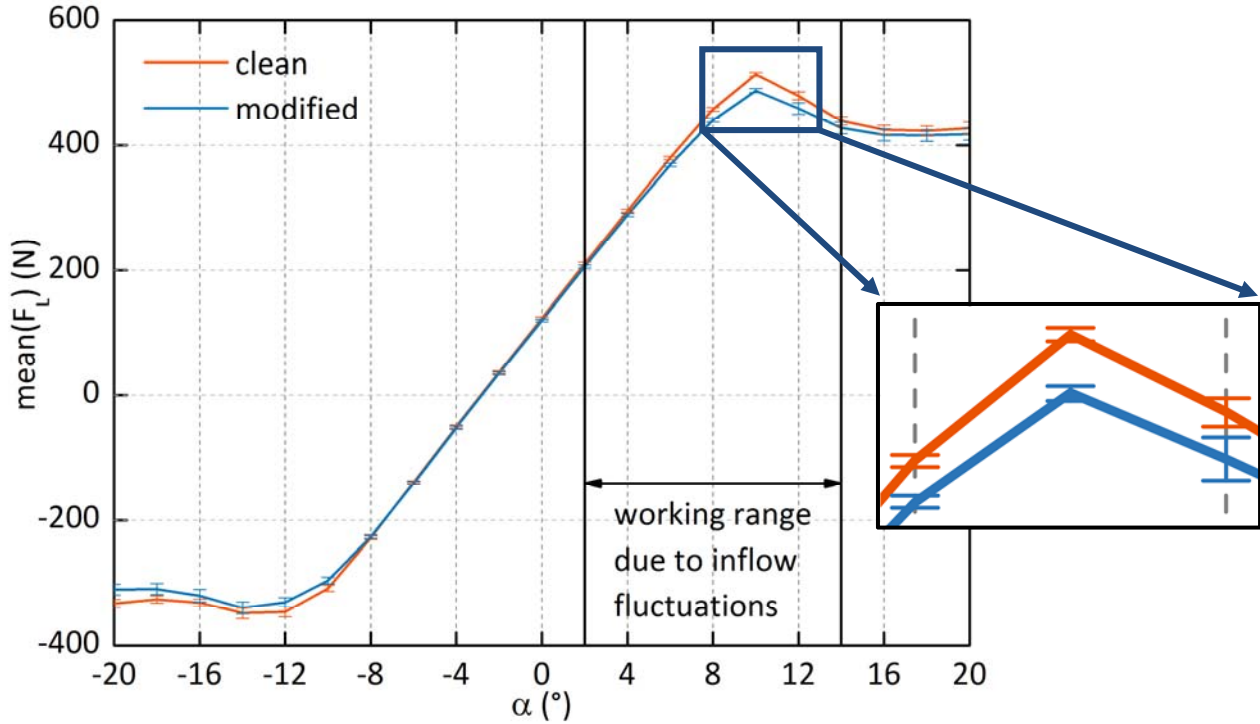


Fig. 9 Lift force over angle of attack of a clean DU 91-W2-250 profile (red) and a modified one with turbulators (blue). The zoom shows the maximum lift range including fluctuations in terms of standard deviation.

Wind turbines usually operate at an effective $\alpha \approx 8^\circ$. The unsteady turbulent atmospheric BL modulates this mean AoA towards fluctuations mainly from $\alpha \in [2; 14]^\circ$. For this reason, lift forces are analyzed in this working range only. Here, the modified airfoil performs consistently inferior to the clean one. Noticeable is an increasing deficit of generated lift by the modified airfoil towards the maximum lift AoA, $\alpha_{max}=10^\circ$, and decreasing beyond. As a maximum lift goes along with maximum energy output, a deficit of 5% at α_{max} appears as unfavorable and should be avoided in general. Unless this effect is used on purpose, known from vortex generators that are applied to an airfoil to stabilize the lift as a trade-off for inferior performance. In order to examine the lift stability, we take a closer look at the maximum lift range (see zoom in figure 9). Therein, a striking difference between the two curves is emphasized. Particularly in the post stall range for $\alpha_{max}=12^\circ$ the fluctuations of lift forces increase tremendously by more than 50% for the modified airfoil. Instead of being stabilized, the lift becomes highly unsteady applying dynamic loads on the airfoil that are highly destructive for rotor blades on the long term.

Closing the first main objective of the present study, IRT is capable of concluding the severity of a defect and its impact on the rotor blade's performance just from the flow formation mapped by the thermogram in a standard experimental setup. Inferior performance is particularly characterized by generating decreased lift along with increased lift fluctuations. A localized consideration of lift fluctuations on operating wind turbines has not been performed so far although being definitely important with regards to fatigue. Thus, in the next chapter a detection of lift fluctuations using IRT is examined.

4 Time-resolved laminar turbulent transition

The motion of the free transition region is of interest, as it corresponds to dynamically changing Re_c and α . With respect to rotor blades, both parameters are modulated by turbulence in the atmospheric BL and their sudden change coincides with dynamic loads. Hence, utilizing IRT in a time resolving way to image transition on rotor blades of operating wind turbines would be a great progress to understand its occurrence and prevent failure due to overload. The challenges of high-speed IRT (HSIRT) measurements consist of a low thermal contrast and high thermal inertia. By now, HSIRT boundary layer studies were performed on elaborately heated surfaces [7] or tried to enhance thermal contrast artificially by indirect difference methods [8]. According to the findings of chapter 3, the drawbacks of employing IRT on an aluminum profile did not prove as serious since distinct flow features are still clearly visible on the thermogram despite of an alleged little thermal contrast. By taking advantage from high thermal conductivity, a time resolved representation of the flow might be mapped by the thermogram as remaining temperature differences from any thermal history are equalized very. In this way, the same experimental setup as for the investigation of evolving turbulent wedges on the DU 91-W2-250 profile is used (see first experiment in chapter 3 and figure 7). By removing the turbulators, the motion of the free transition region can be imaged in the open test section. One snapshot of the emerging free transition is shown in figure 10a for $Re_c=250.000$.

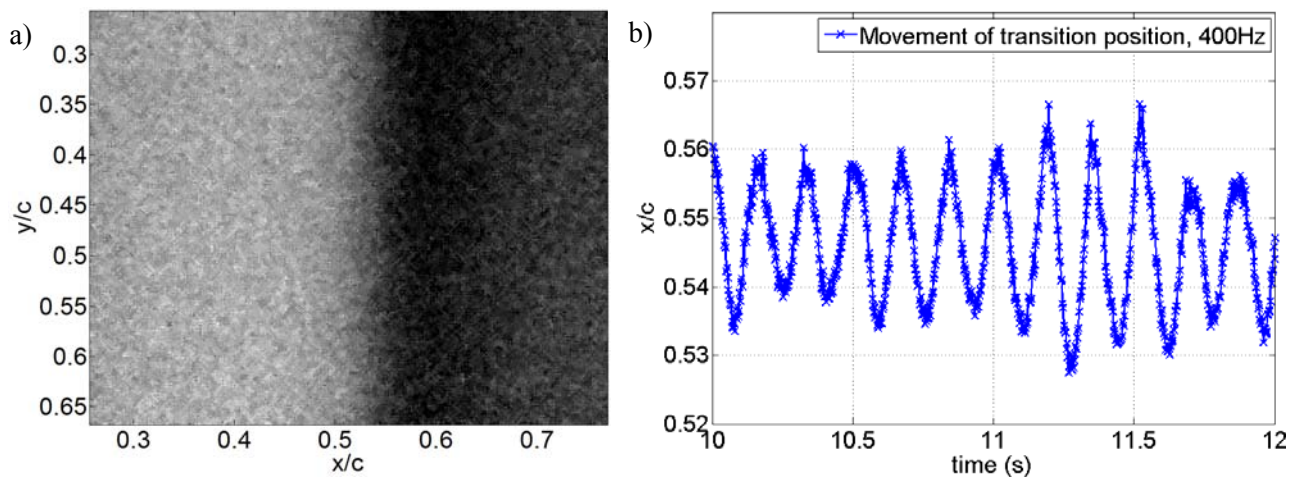


Fig. 10 (a) Thermogram of the onset of transition on a DU 91-W2-250 profile at $Re_c=250.000$ recorded in a lower spatial resolution to enable a (b) temporal tracking of the moving transition line with a sampling rate of 400Hz.

The thermogram reveals a typical temperature profile of an airfoil undergoing transition in a cold environment [9]. The laminar region upstream of $x/c=54\%$ appears brighter/warmer as it applies a lower convective cooling on the airfoil than the turbulent region. The transition coincides with the sudden change from bright to dark at about $x/c=54\%$. The transition line can be defined as the maximal gradient (magnitude) of temperature/greyscale in chordwise direction. In this case it is determined by spatially averaging the gradient in spanwise direction. In order to obtain a time-resolved motion of the transition line the IRT camera is operated at a reduced resolution of 320×256 px and an integration time of 1ms enabling a framerate of 400Hz. The result of tracking the transition line for two seconds is depicted in figure 10b. The position moves in a wave form between $x/C=53\%$ and $x/C=56\%$ with changing amplitudes. Clearly observable is quite a regular sinusoidal shape that is induced by a periodical pumping of the wind tunnel due to the half-open test section (see first experiment in chapter 3). Indeed, the observable 6.8Hz match the outlet's eigenfrequency perfectly at $Re_c=250.000$. The occurring inflow fluctuations cause a relatively strong motion of the transition line implying high fluctuations in lift. An operating wind turbine has to face considerably higher inflow fluctuations, hence a motion of the transition line should appear as well resulting in dynamic loads which should be avoided. Finally closing the second objective of the present study, fluctuations of the transition line on airfoils in a standard experimental setup can be determined by IRT in the wind tunnel.

5 Concluding remarks

The results of the present study qualify IRT as a condition monitoring method for rotor blades of operating wind turbines. In a wind tunnel, the severity of defects and their impact on the airfoil's performance can be assessed by means of the thermogram. Indeed, airfoils suffer from decreased lift along with strong lift fluctuations once defects occur. Certainly, as a final challenge IRT needs to be used in practice on degraded rotor blades with complex damage patterns but first measurements give promising results (see figure 1). Differently from the presentation in this study, only the average position of the transition line can be identified for an operating rotor blade due to a long thermal response time of its composite material. In order to gather temporal information about the transition line's position, the rotor blade's surface needs to be slightly modified. In this way, employing IRT is of academic relevance to better understand the aerodynamic process of transition and conclude possible improvements for rotor blade designs from that. A practical application for condition monitoring appears to be suitable by taking advantage from deicing methods that heat the rotor blade's surface resulting in a low thermal response time. In general, IRT is very easy in application and nevertheless provides a great potential to image a variety of flow phenomena on airfoils even in a practical environment.

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