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IR thermographic visualization of flow separation in applications with low thermal contrast

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HIGHLIGHTS

- Two methods for a thermographic visualization of separated flow are proposed.
- Visualization without explicit additional heating of the measured object.
- Validation with wind tunnel experiments on a circular cylinder and a NACA 63_3-618.
- The underlying approaches are based on a thermographic time series analyses.
- Both methods enable a fast and noninvasive visualization of separated flow.

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ABSTRACT

A measurement method for IR thermographic visualization of separated flow on rotor blades for wind turbines is demonstrated. Flow separation has a negative influence on the performance of airfoils, e.g., at wind turbine rotors. Thermographic flow visualization is a non-invasive measurement technique to identify different flow regimes, but the visualization of separated flow without explicit additional heating of the measured object has not been possible to date. For this reason, a measurement approach with an enhanced sensitivity is presented, which evaluates temporal temperature fluctuations from a thermographic images series by means of the standard deviation as well as the analysis of selected Fourier coefficients. The approach is validated by wind tunnel experiments with a non-heated circular cylinder as well as a 2D 6 digit NACA-airfoil. The flow and measurement conditions are chosen to be similar to wind turbines in operation. As a result, the flow regimes including the flow separation are resolved and are in agreement with reference measurements, while the sensitivity of standard thermographic flow visualization was too low. In addition, the Fourier analyses method results in an improvement of the contrast to noise ratio between turbulent and separated flow by 11.6 % compared to the evaluation of the temperature standard deviation. Further improvements are expected in future when taking the complete spatiotemporal temperature fluctuations into account.

1. Introduction

Flow separation on an rotor blade of a wind turbine is an undesirable phenomenon as it results in a sudden decrease in lift and an increase in drag [31,12]. Furthermore, the resulting periodic shedding of the flow leads to unsteady structural loads and to vibrations [26]. On rotor blades for wind turbines, flow separation is an often present flow state especially near the root of the rotor blade [13]. Beside the negatively affected overall performance, the unsteady loads due to flow separation reduce the lifetime of the wind turbine and cause flow and vibration induced acoustic emissions, which complicate the siting and lower the social acceptance. In order to study the effects and resulting mechanisms close to the real application, a measurement of the flow separation phenomena on rotating wind turbines is demanded.

State-of-the-art methods for determining the location of a separated flow region at wind turbines in operation involve tufts [33], stall flags [3] or oil solutions [21]. However, the placement and precise positioning of the means is a time consuming and costly operation for these methods. Moreover they are invasive and, thus, have an influence on the boundary layer itself, resulting in an affected downstream flow. Since invasive measurement techniques are unsatisfactory and the observation of the rotor blade

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under real conditions is a key task in validating the desired performance of the rotor blade, a novel non-invasive measurement technique is needed that requires no preparation of the rotor blade. For this purpose, the capability of flow separation visualization using infrared (IR) thermographic flow visualization is investigated.

A thermographic measurement has the potential to deliver the similar information as the invasive methods, but is non-invasive, reaction-less and faster (no preparation of the rotor blade). As state of the art, the IR thermographic flow visualization is a known technique for the visualization of different flow regimes in the boundary layer. Based on a temperature difference between the object and the incoming flow, changes in the boundary layer can be distinguished by measuring the surface temperature with a thermographic camera. The surface temperature depends on the local heat transfer between the object and the flow, which is proportional to the skin friction in different flow regimes [27,19,10]. Wind tunnel applications for this method are the localization of the laminar-turbulent transition [9], the identification of laminar separation bubbles [23] or the visualization of a turbulent separation [10]. For a sufficient contrast in the thermographic images, the observed object is usually externally [2] or internally [20] heated or cooled. Additionally an insulation against the internal thermal conductivity of the object enhances the contrast and improves the thermodynamic response behavior [32]. The successful transfer of these techniques from the laboratory to the area of operation is reported in particular regarding the detection of the laminar-turbulent transition, e.g., for in-flight experiments on aircraft wings [4] as well as for measurements on rotating helicopter blades [15,18] and on rotating wind turbine blades [7]. Recently, the automated detection of the laminar transition is proposed by Crawford et al. [5] and by Joseph et al. [17] in order to gain also quantitative information, e.g., within long lasting wind tunnel campaigns. Furthermore, an image processing is presented in Raffel et al. [28] that addresses the thermodynamic response of the object surface for enabling the measurement of fast position changes of the laminar-turbulent transition.

For the thermographic detection of the laminar-turbulent transition, heating power levels between several hundred [17] up to a few thousand [18,32] $\mathrm{W\,m^{-2}}$ are reported. This results in a temperature difference between the tested object and the flow of a few Kelvin. Gardner et al. [8] recently described a method for the dynamic and static stall detection with thermographic measurements by the evaluation of the spatial standard deviation from a high-frequency sampled series (107 Hz) of consecutive differential thermography images. With the described method, spatial resolved information of the flow conditions can be obtained at temperature differences between the measurement object and the flow in the order of 10 Kelvin. However, on wind turbines in operation, there is no feasibility for a uniformly active heating of the rotor blade and a thermal insulation of the surface of the rotor blade cannot be installed. The available thermal contrast between the rotor blade and the incoming flow is only based on the absorbed solar radiation, which can be estimates to $175\,\mathrm{W\,m^{-2}}$ during the summer (cf. Section 2). The resulting relatively low temperature difference can lead to a poor image contrast, which makes it difficult to visualize different flow regimes [6]. Under sufficiently sunny conditions it is possible to detect a satisfactory difference between laminar and turbulent flow regimes and to localize the transition between both regimes [6]. The ability of the sun for heating the observed object has also been proven by Richter and Schülein [30]. However, flow separation on wind turbine rotor blades is not detectable. As a result, the contrast of the thermographic flow visualization has to be increased with respect to the flow separation phenomena for enabling the visualization of separated flow.

For this reason, a novel thermographic measurement approach is demonstrated, where the small temperature fluctuations within a time series of thermographic images are evaluated. This measurement approach, which is based on time-resolved IR thermography, determines temporal temperature variations in order to allow the identification of separated flow regions even at conditions with low thermal contrast. For validating the measurement approach, wind tunnel measurements were conducted on a non-heated, non-isolated circular cylinder in crossflow as well as on a 6 digit NACA-airfoil. First the measurement approach is explained in Section 2. After the subsequent description of the experimental setup in Section 3, the thermographic measurement results are presented in Section 4, which are validated by mean surface pressure measurements, oil flow visualization and acoustic measurements in the boundary layer for the cylinder measurements. The article closes with a summary and outlook in Section 5.

2. Measurement approach

With measurements on a wind turbine in operation in mind, the measurement approach deals with the enhancement of the contrast between turbulent and separated flow to distinguish these regions without an additional heating or coating of the rotor blade. The approach includes the acquisition and the evaluation of a time series instead of a single thermographic image. By that, small temperature differences in terms of temperature fluctuations in time are visualized by a previously executed image processing. The underlying hypothesis of the measurement approach is that regions of laminar, turbulent and separated flow can by distinguished by differences of the measured temperature fluctuations.

Fig. 1 illustrates the different flow regions in the boundary layer around a circular cylinder in the supercritical regime above the critical Reynolds number $Re_{crit} = 4.0 \times 10^5$ [31]. The angular positions are specified by the angle ϕ around the cylinder, starting at

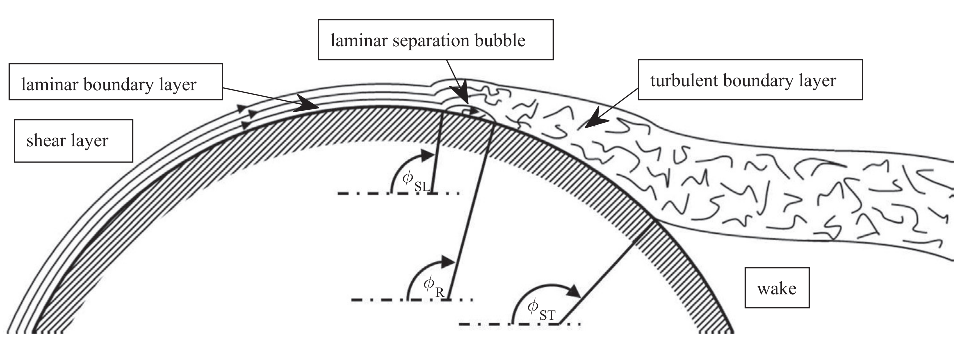

Fig. 1. Schematic sketch of the different flow regions in the boundary layer around a circular cylinder in the supercritical regime above the critical Reynolds number $Re_{crit} = 4.0 \times 10^5$ [31], with the angular positions for a laminar separation ϕ_{SL}, a reattachment of the flow ϕ_R and a turbulent separation ϕ_{ST}.