Indirect assessment of disturbance on rotor blades with infrared thermography

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Abstract

Surface disturbances on airfoils can trigger premature laminar–turbulent transition and generate characteristic wake structures. This work investigates a thermographic approach for estimation of disturbance size under realistic aerodynamic conditions at Re = 4 × 10^6. Cylindrical disturbance elements with variable aspect ratios are integrated into the suction side of an airfoil, and the resulting wake structures are captured using infrared thermography. The results demonstrate the feasibility of wake-angle-based inverse characterization of local surface disturbances.

1. Introduction

Surface disturbances on wind turbine rotor blades, such as erosion, insect contamination [1], or manufacturing imperfections, can disturb the boundary layer and trigger premature laminar--turbulent transition, resulting in aerodynamic performance losses [2]. Since even small local disturbances in milimeter scale may already affect the flow condition, non-invasive measurement techniques are required to detect and characterize such defects during operation in order to avoid turbine downtime and associated power losses.

Infrared thermography (IRT) has been established as a contactless method for flow visualization on airfoils by measuring surface temperature differences associated with different flow states. Previous studies have shown that disturbance-induced wake structures can be visualized with IRT and that their appearance is sensitive to the disturbance geometry [3]. However, most existing investigations have mainly focused on qualitative observations, limited parameter variations, and low Reynolds number conditions (Re < 1 × 10^6) [4]. In particular, the quantitative inverse estimation of disturbance characteristics from thermographic wake patterns at large Reynolds number conditions (Re > 1 × 10^6) remains insufficiently investigated.

Therefore, the present work investigates an indirect thermographic approach for inverse characterization of local surface disturbances on an airfoil under realistic aerodynamic conditions at a Reynolds number of approximately Re = 4 × 10^6. Thermographic wake structures induced by cylindrical disturbance elements are analyzed with respect to their sensitivity to disturbance size and their feasibility for inverse estimation.

2. Measurement principle

Cylindrical additive type disturbance elements are integrated into the suction side of the airfoil with chord length c and used as a generic representation of a local surface defect. The disturbance geometry is described by its diameter d and height h. In the present work, the disturbance diameter was kept constant at d/c = 3.75 × 10^{-3}, while h was varied to obtain aspect ratios in the range of 0.05 ≤ Γ ≤ 1, where the aspect ratio is defined as Γ = h/d.

Infrared thermography was applied to visualize the wake structure induced by the disturbance. Since laminar and turbulent boundary layers show different convective heat transfer behavior, a defect-induced change in the flow state becomes visible as a temperature pattern on the airfoil surface. The local disturbance can therefore be indirectly assessed through its downstream thermographic wake.

In this work, the wake opening angle θ is used as a characteristic wake parameter. The wake region is approximated as a wedge-shaped structure, and its upper and lower boundaries are extracted from the thermographic image with edge detection algorithm. These boundaries are fitted by two straight lines with least square approach, and θ is defined as the angle between them, see **Figure 1**. The relationship between θ and the disturbance aspect ratio Γ is then used for inverse size estimation.

3. Results

For the selected representative additive disturbance configuration, the wake opening angle θ shows a clear increasing trend with increasing disturbance aspect ratio Γ. This indicates that the thermographic wake structure responds systematically to the disturbance size. The measured wake angle can be described by a fitted asymptotic exponential function, which establishes a quantitative relationship between the thermographic wake response and the disturbance aspect ratio. Based on this fitted forward relation, the aspect ratio Γ was estimated inversely from the measured wake angle θ. The corresponding fitted function and inverse estimation results are shown in **Figure 2**. The inverse-estimated values follow the ideal relation with a mean relative systematic error of 15.98 % in terms of Γ, demonstrating that the wake opening angle can be used as a characteristic thermographic parameter for inverse size estimation in this configuration.

4. Conclusion and outlook

The present work demonstrates the feasibility of using thermographically visualized wake structures for inverse estimation of local surface disturbance size under realistic aerodynamic conditions. For the investigated representative configuration, the wake opening angle θ shows a clear relationship with the disturbance aspect ratio Γ and enables a quantitative inverse estimation of the disturbance size.

However, the present study is restricted to a representative configuration with fixed disturbance diameter, position, and type. In a realistic application, these parameters may vary simultaneously and influence the thermographic wake pattern. This multi-parameter measurement problem remains an open challenge. In addition, the influence of the object geometry should be investigated further. Therefore, future work will focus on additional disturbance configurations, more realistic disturbance geometries, and a more detailed evaluation of geometry-related effects on the inverse estimation approach.

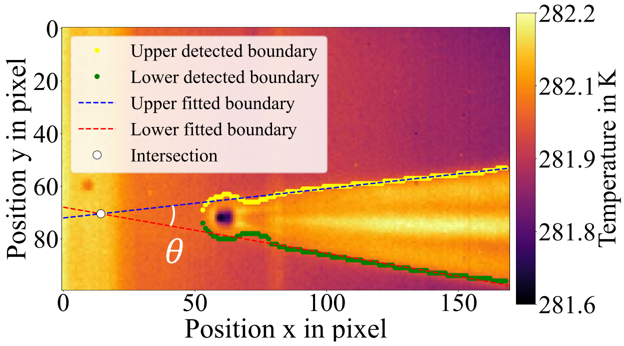
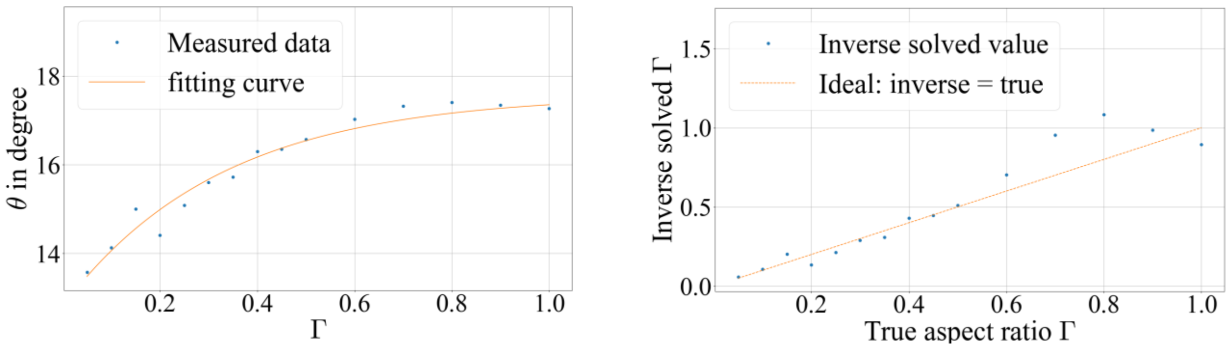


Figure 1. Thermographic wake structure with extracted wake boundaries and wake angle θ.



(a) **(b)**

Figure 2. Forward model fitting and inverse estimation of the disturbance aspect ratio based on the wake opening angle θ. (a) Forward model fitting of θ as a function of Γ. (b) Inverse estimation of Γ based on the measured wake angle θ.

References

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