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THE WAKE FLOW CHARACTER OF A SINGLE CYLINDER ROUGHNESS ELEMENT IN THE BOUNDARY LAYER ON A FLAT PLATE

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ABSTRACT: An incompressible flat plate boundary layer experiment has been conducted to analyze the critical height of a roughness element on a wind turbine blade surface. A single cylinder roughness element was used to simulate the surface roughness, and then the critical height of the roughness element was determined using the results of transition detection. The 2-D velocity field in the symmetry plane of the cylinder element was measured with micro-PIV, after which the velocity fields downstream the cylinder element were analyzed. Tests were carried out on a zero pressure gradient flat plate with an elliptical leading edge profile whose axial ratio is 1:12. The wind speed is $U_\infty = 11.25 \text{m/s}$, the cylinder element was placed at $X=400 \text{mm}$ downstream of the leading edge, the local Reynolds number was $Re_x=3.08 \times 10^5$. The diameter of the roughness element is 5.5mm, the height of the roughness element $k$ is changed from 0.4mm to 1.3mm, the characteristic Reynolds number $Re_k$ ranges from 300 to 1000. The following conclusions have been obtained: 1. For the local Reynolds number $Re_x=3.08 \times 10^5$, the critical height of the roughness element is $k=1\text{mm}$, the corresponding critical Reynolds number $Re_k$ is 770, and the dimensionless critical roughness height is $k/\delta_99=0.3$; 2. There is a reverse flow area behind the critical roughness element; this reverse region ranges from $X=400 \text{mm}$ to about $X=416 \text{mm}$; the boundary layer stays laminar downstream of the reverse flow zone.

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 in addition to uncontrolled boundary layer transition and stall arising from frequently changing ambient flow conditions can cause significant power loss and unfavorable dynamic loads.

On the other hand, scaled models are commonly used in the aerodynamic experimental research on the fixed wing aircraft or propeller, due to the scale effect, transition location on the test models is different from that on the full-scale wing. In order to simulate the boundary layer flow condition of the test models, DRE (distributed roughness elements) are commonly used to fix boundary layer transition in experiments. The DRE should be large enough to trigger the transition while producing minimal drag. Consequently, it is important to investigate the problems about roughness-induced boundary layer transition. The results may support to determine the need for maintenance of the wind turbines by the engineers. And it can also guide experimenters to optimize the size of DRE for different applications.

The early investigations about the roughness-induced boundary layer transition were mainly accomplished by wind tunnel tests [1][2]. In their research on the mechanism of boundary layer transition, Schubauer and Klebanoff [2] measured the half-angle of the turbulent wedge induced by a
single cylindrical roughness element, and the detailed flow feature around the turbulent wedge was measured by using a hot-wire anemometer.
Owing to the availability of large-scale computing resources, direct numerical simulation (DNS) on the laminar-turbulent transition became possible in the last decade. Calculations of the roughness-induced transition were performed in the low and high-speed regime [3][4][5]. DNS has the advantage of providing detailed information on the flow structure, but it requires large computational efforts, and individual studies can only cover a small portion of the large parameter space involved in roughness-induced transition [6].

With the development of flow visualization measurement technology, a large number of non-intrusive measurement techniques for boundary layer transition have been put into application, including oil film interferometry (OFI), temperature sensitive paint (TSP), and infrared thermography (IRT). OFI was successfully applied in wind tunnel experiments to full-scale tilt rotor blades [7] and to high-speed model propeller blades [8]. TSP was also successfully applied on high-speed model propeller blades [9].
The IRT was first used in the 1960s and 1970s, particularly for re-entry vehicles where high enthalpy flows provided enough signal for the relatively insensitive infrared cameras of that time [10]. With the improvement in sensitivity, IR has been used extensively in convective heat transfer measurements in general [11] and in wind tunnels in particular [12]. Investigations of IR for boundary layer transition measurement were carried out both in wind tunnel and in-flight experiments by Zuccher. An automated technique for extracting quantitative transition location from raw IR images is proposed in [13][14]. IR measurements on a rotating aerodynamic experiment were carried out by [15]. Raffel and Merz [16] proposed the differential infrared thermography (DIT) technique for the detection of the location of transition in the unsteady boundary layers on a pitching airfoil and on a rotating blade under cyclic pitch. Most recently, transition detection by high-speed infrared thermography was successfully demonstrated on model and full-scale helicopter rotors in hover condition [17][18]. Today’s infrared thermography has the advantage of high temperature resolution (~0.02 K), as compared to temperature-sensitive paint, which has a precision resolution of ~0.1 K [19].
In this paper, a single cylinder roughness element was used to simulate the surface roughness. The critical height of the roughness element was determined by the results of the IR transition detection. The velocity field in the symmetry plane of the roughness element was measured by micro-PIV to analyze the wake flow character of the roughness element at the critical height.

2 Experiment description

2.1 Experimental setup
The transition induced by the roughness elements was detected by an IR camera, and the critical height of the roughness element was determined by the results of the transition detection.
In order to analyze the wake flow character of the roughness element at critical height the velocity field in the symmetry plane of the roughness element was measured by micro-PIV. The PIV camera was placed on a rail parallel to the flat plate, which allows measuring the velocity field at several sections downstream of the roughness element. The wind speed is $U_{\infty} = 11.25$ m/s, the cylinder element was placed at the section $X=400$ mm downstream of the leading edge, the local Reynolds number was $Re_x = 3.08 \times 10^5$. The diameter of the roughness element is 5.5 mm, the height of the roughness element $k$ is changed from 0.4 mm to 1.3 mm, the characteristic Reynolds number $Re_k$ ranges from 300 to 1000.

2.2 Test model and facilities
The test model is a zero-pressure gradient flat plate; its leading edge has an elliptical profile with an axial ratio of 1:12. The thickness and length of the flat plate are 15 mm and 1000 mm respectively. The IR camera is a FLIR A655sc, its pixel resolution is $640 \times 480$, and its temperature sensitivity is $35$ mK. The max sampling rate of this IR camera is 50 Hz. In this experiment a sampling rate of the IR camera of 25 was used. A halogen lamp was used to heat the model surface to produce a temperature difference between the model and the airflow. The pixel resolution of the PIV camera is $2048 \times 2048$, the sampling rate is 10 Hz. A long range microscope was used to be able to capture a small field of view. The working distance of the microscope ranges from 300 mm to 1200 mm, correspondingly the field of view ranges from $3\text{mm} \times 3\text{mm}$ to $10\text{mm} \times 10\text{mm}$.

3 Micro-PIV measurements

3.1 Measuring features
Fig. 3. shows a typical distribution of seeding particles for PIV from the laminar to the turbulent boundary layer. It can be clearly seen that there is a lack of seeding particles in the near-wall region of the laminar boundary layer, which results in the fact that the particle density in the laminar region is not high enough to be able to calculate the displacement vector using cross-correlation algorithms directly.
3.2 Data processing method

Two methods were investigated to calculate the velocity field from the particle images. In the first method, Particle Tracking Velocimetry (PTV) was used to calculate particles’ displacement vectors from each particle image pair. The time averaged velocity profile is calculated from the particle displacement vectors of 50 particle image pairs (Fig.4).

For the second method virtual PIV recordings (with sub-images A and B) were produced by overlaying 50 instantaneous experimental A and B sub-images respectively. The displacement vector field was obtained from the virtual PIV recording through the cross-correlation algorithm.

3.3 Measurement validation

In order to validate the micro-PIV measurement results on the flat plate, the laminar boundary layer profile was measured at X=200mm, and the results are compared with the Blasius boundary layer profile.

![Fig. 5. Laminar boundary layer profile measurement results, U=10m/s, X=200mm](image)
Fig. 5. shows that the laminar boundary layer profile measured by micro-PIV agrees well with the Blasius boundary layer profile.

4 Results and discussion

The measurement results contain IR transition detection results, the near wall flow field on the clean flat plate from X=350mm to X=700mm, and the near wall flow field on the plate downstream the roughness elements from X=400mm to X=700mm.

Fig. 6. shows the plate surface temperature maps downstream of roughness elements with different height. When the height of the roughness element is greater than 1, a significant turbulent wedge can be observed.

Fig. 6. IR transition detection downstream of roughness elements of different height

Fig. 7. shows the wake flow of the roughness element (k=1mm) in the boundary layer. A reverse flow area behind the roughness element can be seen, which ranges from X=400mm to about X=416mm.

Fig. 7. Wake flow of the roughness element k=1.0mm at \( U_\infty = 11.25 \text{m/s}, \text{Re}_x=3.08 \times 10^5 \)

Fig. 8. shows the boundary layer velocity profiles at natural transition and fixed transition conditions, the height of the roughness element is k=1mm. Obviously, the flow state downstream the roughness from X=450mm to X=600mm stays laminar, and it changes to turbulent flow at about X=700mm.

Fig. 8. Velocity profiles downstream of roughness elements
5 Conclusion

The single cylinder roughness element induced transition on incompressible flat plate flow was measured by IR and micro-PIV; the critical height of the roughness elements was determined. There are the following main conclusions.

1. For the local Reynolds number $Re_x=3.08 \times 10^5$, the critical height of the roughness element is $k=1\text{mm}$, the corresponding critical Reynolds number $Re_k$ is 770, and the dimensionless critical roughness height is $k/\delta_{99}=0.3$.

2. There is a reverse flow area behind the roughness element, and this region ranges from $X=400\text{mm}$ to about $X=416\text{mm}$ and the boundary layer stays laminar downstream of the reverse flow zone.

3. The transition position on the clean flat plate is $X=750\text{mm}$, when $U_\infty=11.25\text{m/s}$, the roughness element of $k=1\text{mm}$ moves the transition forward to $X=700\text{mm}.$
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References


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