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Self-starting characteristics of wind turbines with passive flow-control devices on rotor blades

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SUMMARY:
There are many adverse issues caused by flow separation on wind turbines with horizontal and vertical axes of rotation. Both types of wind turbines experience structural fatigue, but in addition, vertical-axis wind turbines are also characterized by self-starting issues at lower wind velocity. One of the possibilities to mitigate this issue is the application of passive flow-control devices on wind-turbine rotor blades. The goal of the present study is accordingly the analysis of a possible increase in the aerodynamic performance of NACA 0021 airfoils for the entire range of the Angle of Attack (*AoA*) from 0º to 360º. This work was performed in a wind tunnel using rotor blades equipped with vortex generator (VG) and Gurney flap (GF) devices. Experimental results encompass aerodynamic force and moment coefficients for NACA 0021 airfoil equipped with VGs and GFs. These devices proved to improve flow characteristics and to reduce adverse effects of flow separation.

Keywords: Wind turbines, Passive flow-control devices, Wind-tunnel experiments

1. INTRODUCTION

The conversion of wind into electrical energy is performed by wind turbines, mostly by horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). For the wind energy production to be sustainable and feasible, it is necessary to optimize dimensions, strength, lifetime and other structural parameters of wind turbines.

In urban areas, small multi-kW VAWTs proved to be more suitable than HAWTs. In comparison with HAWTs, VAWTs do not require the adjustment of the rotation axis when wind changes direction, and they are characterized by a simple design, Bianchini et al. (2022).

The disadvantage of VAWTs, however, is the fact that the blades are subjected to the entire range of *AoAs* and prone to reduced performance. This occurs for parked wind turbines but also for rotation at low tip speed (velocity) ratios (*TSR*), which may further deteriorate flow characteristics on airfoils. This phenomenon requires the self-starting wind velocity to be greater than in the standard working conditions.

A relatively small improvement in the self-starting characteristics may yield a substantial increase in the VAWT efficiency according to Goncalves et al. (2022). This fact created a motivation to try to improve self-starting characteristics of VAWTs further by using passive flow control devices (PFCDs).

Frunzulica et al. (2014) suggested that various PFCDs on NACA 0012 airfoils may enhance self-starting characteristics and increase the performance of VAWTs at low rotation velocity. Acarer (2020) was successful in significantly increasing C_L/C_D ratio of DU12W262 airfoil by introducing a slot concept. Wu et al. (2021) studied the effect of VGs on the transition area of rotor blades and indicated a delayed flow separation that improved the output torque. The effect of GF size on the VAWT performance proved substantial, Zhu et al. (2021).

To address self-starting characteristics properly, it is necessary to know beforehand the aerodynamic forces and moments acting on airfoils with and without PFCDs. Hysteresis and bistable states of the flow may occur for some *AoAs*, Holst et al. (2018).

Aerodynamic forces acting on parked HAWTs have not yet been sufficiently studied. A knowledge gap is identified for HAWTs equipped with PFCDs. This applies particularly on smaller HAWTs in urban areas, which in certain weather conditions, e.g., storms, may be exposed to high wind velocity, although they are designed for relatively low wind velocity.

Given a remarkable lack of information on the aerodynamic characteristics of airfoils equipped with VGs and GFs in the entire range of *AoA*, this topic was experimentally studied in our present work. The analyzed parameters are aerodynamic forces and moments. The results are relevant for self-starting characteristics of VAWTs and for aerodynamic forces acting on parked HAVTs.

2. METHODOLOGY

Experiments were performed in a closed return wind tunnel with an open test section characteristic for aerodynamic studies on airfoils, e.g., Du et al. (2015). A wing with a constant chord based on the NACA 0021 airfoil was placed horizontally in the test section as shown in Figure 1.

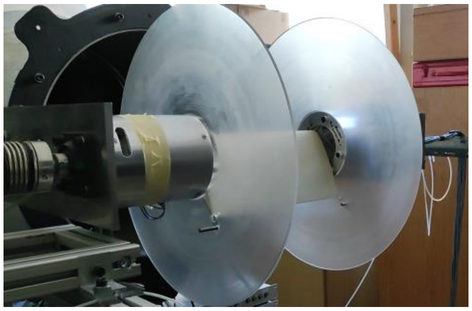

Figure 1. NACA0021 airfoil in the test section of a closed return wind tunnel

The *AoA* was varied by rotating the wing in the airflow. On the wing surface, pressure taps were implemented to determine surface pressure distribution. PFCDs were subsequently mounted on the airfoil, i.e., VGs were placed on 15% of the airfoil cord, and 2 mm long GFs were used across the entire wingspan. The effect of VGs and GFs was studied separately, i.e., when only one of these PFCD types was employed on an airfoil.

A Pitot-static tube was used to determine the mean flow velocity. Air temperature, density, and relative humidity were recorded simultaneously to determine the Reynolds number (*Re*). *Re* was set to be $Re \sim 1.8 \cdot 10^5$. The *AoA* for steady flow was studied from 0º to 360º at the incremental step of 1º and back from 360º to 0º. It was accordingly possible to analyze hysteresis in pressure for increasing and decreasing *AoA*.

At each *AoA*, pressure samples were recorded during 1 s at a sampling rate of 5 kHz. The pressure was recorded at 32 chordwise locations on the airfoil, i.e., 15 points on the bottom airfoil surface and 17 on the top airfoil surface. The obtained results were analyzed in terms of the lift coefficient c_L and drag coefficient c_D of an airfoil, which were obtained by integrating pressure distribution along the top and bottom surface of the studied airfoil. The drag coefficients only show the pressure drag where the surface friction is not considered.

3. RESULTS

The obtained c_L and c_D are reported for various *AoAs* (α) in Figures 2 and 3, respectively.

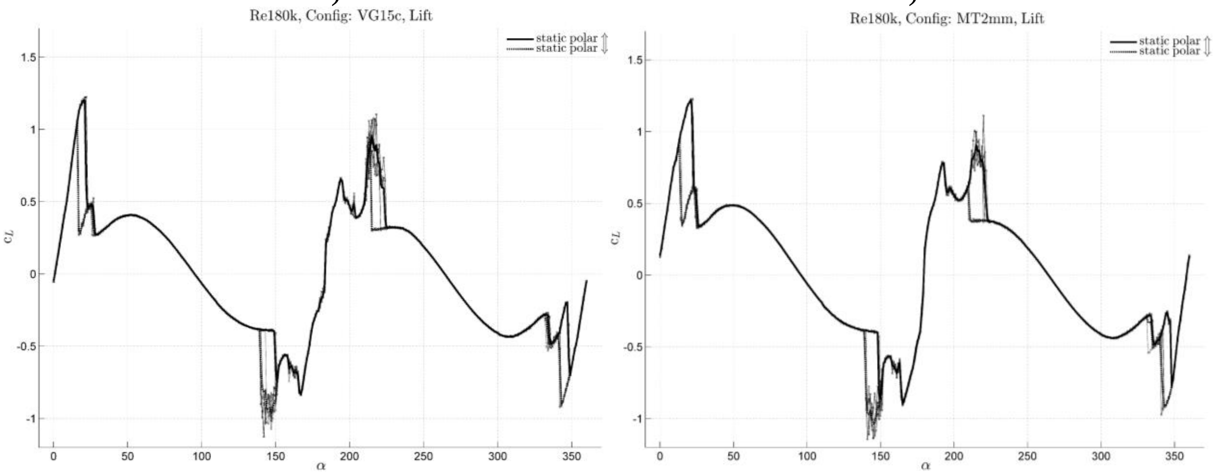
a) b)

Figure 2. c_L of the NACA0021 airfoil with a) VGs and b) GFs

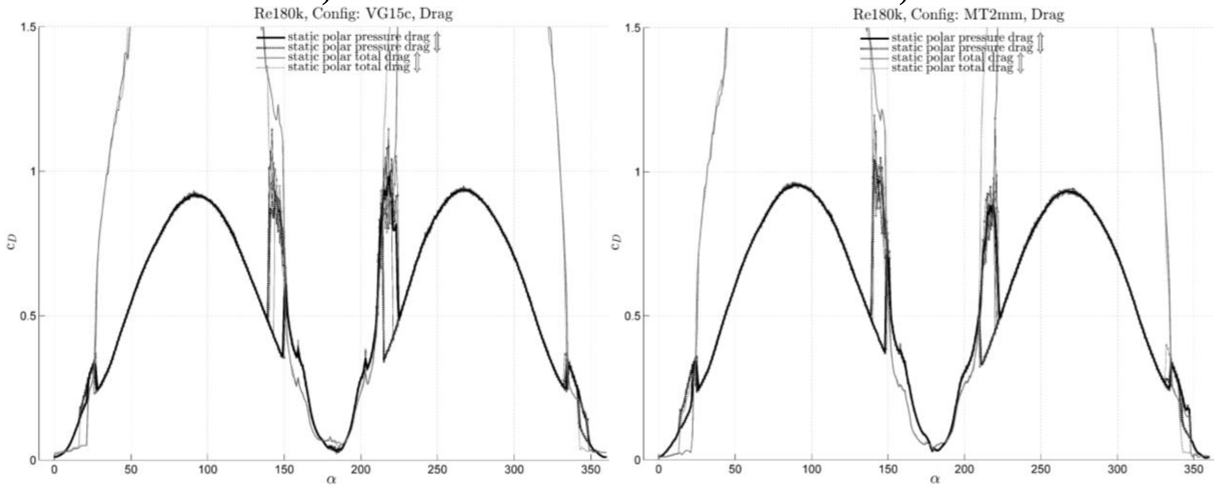
a) b)

Figure 3. c_D of the NACA0021 airfoil with a) VGs and b) GFs

Solid line denotes c_L obtained for α increasing, while the scattered line is for decreasing α. It may be observed that GFs and VGs yield an increased peak $c_L \sim 1.25$, while the peak c_L is reduced to approximately 1.05 in the baseline configuration without GFs and VGs, a trend in accordance with Holst et al. (2019).

Flow separation on an airfoil equipped with PFCDs occurs more abruptly than compared to the baseline configuration. There are four main zones where the c_L hysteresis is present. In each configuration, when α increases, flow separation occurs at some specific α, but this α is substantially lower for decreasing α experiments. The GF configuration has the maximal c_L, while the VG configuration exhibit minimal hysteresis in c_L.

In general, c_D does not change significantly when GFs or VGs are added on the airfoil. c_D is slightly larger when GF is positioned on the bottom airfoil surface. c_D hysteresis may be observed in four regions. Two regions close to $\alpha = 0^{\circ}$ exhibit almost no hysteresis, while two regions close to $\alpha = 180^{\circ}$ are approximately one order of magnitude higher.

4. CONCLUDING REMARKS

Experiments were performed in a wind tunnel to study passive flow-control devices for rotor blades for improvement of the self-starting characteristics of wind turbines. Pressure distribution on the NACA0021 airfoil equipped with PFCDs in the entire range of *AoAs* was analyzed. The Reynolds number was $Re \sim 1.8 \cdot 10^5$ thus indicating fully turbulent flow conditions. The lift and drag coefficients, c_L and c_D, respectively, were obtained by integrating the pressure distribution on the airfoil. By introducing VGs and GFs, the aerodynamic behavior of the airfoil was significantly improved, which is most evident in the increase of the maximum c_L and the delay of flow separation without a significant increase of c_D. The application of VGs reduced the c_L hysteresis.

Based on these results, it is clear that the application of VGs and GFs may improve the self-starting characteristics of wind turbines, which is the topic of the subsequent work. Further work will also address aerodynamic characteristics of airfoils at various *Re*, both for VAWTs and HAWTs.

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