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# Aerodynamic performance analysis of slotted airfoils for application to wind turbine blades

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ABSTRACT

In this paper we explore the improvement of aerodynamic characteristics of wind turbine airfoils under stall conditions through passive boundary layer control using slots. Baseline S809 airfoil was modified based on CFD calculations. An extensive 2D-numerical study has been done to analyze the effects of slot's location, width and slope and the best configuration was determined. Simulations were done using steady RANS equations; the turbulence closure model has been chosen among four possible choices (standard $k$–$\varepsilon$, Spalart–Allmaras, $k$–$\omega$ and $k$–$\omega$ *SST*) based on comparison with experimental results. The lift and drag coefficients and lift-over-drag ratio are compared for the different configurations. The results show that the control system improves aerodynamic performance only over a specific range of angles of attack. However, a significant penalty is observed on the airfoil efficiency for the final configuration, this penalty results from higher drag than the baseline airfoil at low angles of attack. At moderate and high angles of attack, from 10° to 20°, the slot configuration outperforms the baseline configuration.



## 1. Introduction

The importance of increasing the share of clean energy sources is increasing due to demonstrated negative environmental effects of fossil fuels (Varol et al., 2001). Wind energy is becoming a significant contributor to the world's electrical energy generation systems and it is the fastest growing source of energy in the world today. In 2014, a new record of more than 51 GW of wind power has been installed, bringing the global total close to 370 GW. Wind energy has become not only the renewable energy of choice, but also the least-cost option for new installed power plants. Thousands of wind turbines are installed every year around the world and feed with electrical power the local or interconnected electricity grids. Germany set a new record, installing nearly 5300 MW in 2014 while China installed 23 GW of new wind power in a single year according to the last report of the Global Wind Energy Council (2014).

The motivation for the present research is to optimize the performance of wind turbine rotors by using different geometries of slotted airfoils (Chehouri et al., 2015). According to (Ju and Zhang, 2012) the wind turbine airfoil should satisfy the following aerodynamic requirements:

1. High lift-to-drag ratio ($C_l/C_d$) and high lift coefficient;
2. Good performance during stochastic behavior of the wind;
3. Low performance sensitivity to leading edge roughness.

Different optimization techniques have been used to design airfoils that satisfy these conditions (Li et al., 2010; Bizzarrini et al., 2011; Grasso, 2011; Grasso, 2012; Sagol et al., 2013; Fuglsang and Madsen, 1999). However it is difficult to have an airfoil shape that will adequately satisfy all these requirements over the whole operation regimes of the wind turbine. The modification of blade pitch and variable speed are the mechanisms that allow a better power extraction when wind regime changes. One inconvenient of the pitch systems is that it is unable to cope with the highly dynamic and non-uniform inflow which interacts with large wind turbine rotors (Pechlivanoglou, 2013).

Aerodynamic performances (lift-over-drag ratio, $C_l/C_d$, and maximum lift coefficient, $C_{lmax}$) and stall conditions are strongly affected by the viscous effects, concentrated in the boundary layer. Therefore, numerous studies demonstrated the influence of the boundary layer on lift and drag forces, especially on wind turbines

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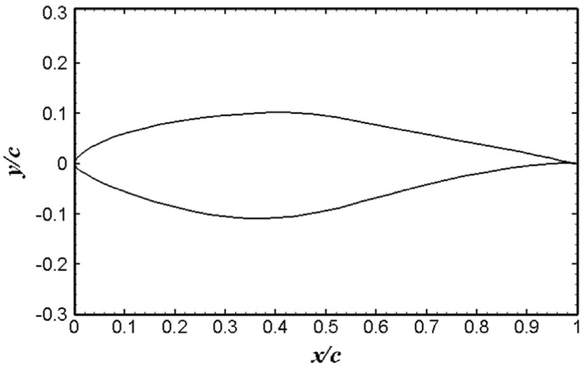


**Fig. 1.** NREL S809 airfoil geometry.

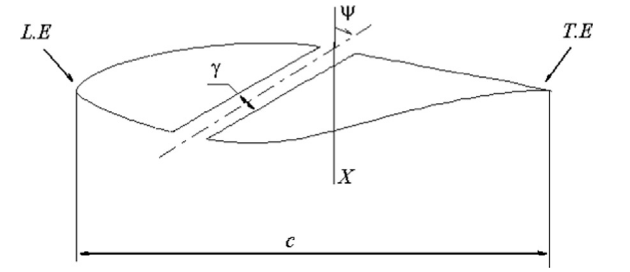


**Fig. 3.** Slot geometric characteristics (c: Airfoil chord, LE: Leading edge, TE: Training edge, $X$: Slot location, $Y$: Slot width $\psi$: Angle between slot axis and chord normal).

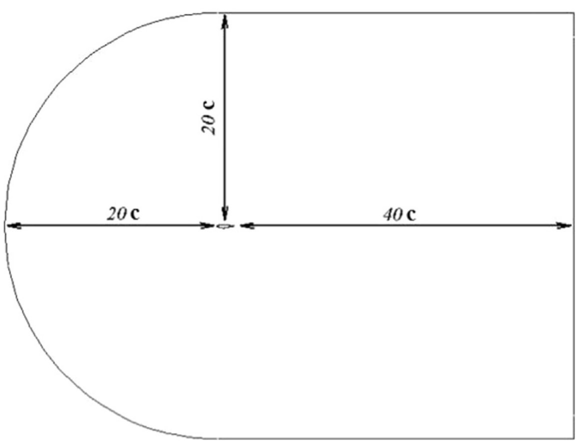


**Fig. 2.** Computational domain.

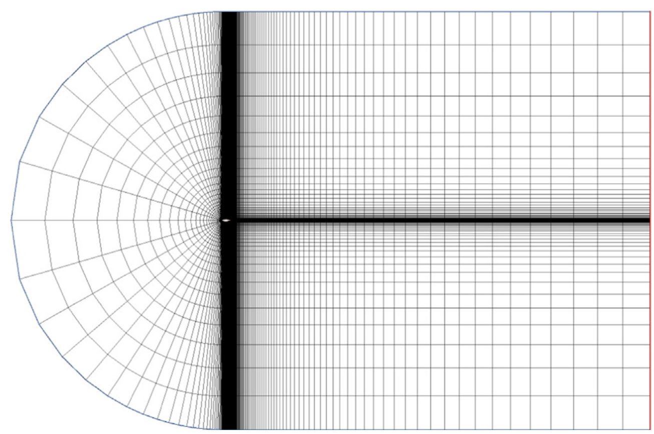

**Fig. 4.** Structured C-type mesh.

and wings (Van, 1996; Hoerner and Borst, 1985). The flow separation control and boundary layer control are methods for the boundary layer management aimed to increase lift-over-drag ratio. Boundary layer control methods are divided in two categories: passive and active flow separation control. Passive control does not require auxiliary power or a control loop. Vortex generators are passive flow control solutions. The first experiments on conventional passive vortex generators were reported by Taylor (1947) and Bruynes (1951). This type of vortex generator normally consists of a row of blades or airfoils, slightly higher than the boundary layer thickness, set at an angle against the on-coming flow. These devices generate vortices that propagate downstream enhancing the mixing of the boundary layer with the free flow. This way, the boundary layer remains attached on the airfoil. The Gurney flaps were discovered by Dane Gurney (Houghton and Carpenter, 2006). The Gurney flap is a simple flat plate in the order of 1% of the chord length, located perpendicular to the pressure or suction side of the airfoil at the trailing edge, this devise increases the lift coefficient of airfoil while a relatively small increase in drag coefficient is observed (Liebeck, 1979).

The slotted airfoil was initially introduced by Handley Page (Inventor and Parker, 1920) in Britain and Lachmann in Germany (Houghton and Carpenter, 2006) but the first detailed study was performed by Weick (1933). In their study, they examined various combinations of slot locations aiming to identify the optimal configurations. Ramzi and AbedErrahmane (2013) have studied the effect of the position, thickness, and the slope of the slot on a cascade of a highly loaded compressor. Their results show, based on a 2D analysis, a maximum reduction of 28% of the loss ratio and an increase of 5° in the flow deflection angle. Application of slotted airfoils to a UH-60A helicopter has been explored by Lim (2002). Baseline SC1095 and SC1094 R8 airfoil characteristics were modified based on CFD calculations of an A3c slotted airfoil; this study shows that use of slotted airfoil increases maximum thrust of the UH-60A helicopter by up to 25%, but a significant drag increase was observed at low angles of attack. Narsipur et al. (2012) used two-dimensional CFD simulations to study a multi-element airfoil system for wind turbine blades with one main element and two flaps by varying flap deflection, gaps and overhangs. Their results show that changes in the flap gap, overhang and deflection can increase the aerodynamic efficiency of the multi-element airfoil system. However, there is no fixed location of the flaps that is optimal for all operation regimes of the wind turbine blade. Ragheb and Selig (2011) found that a multi-element airfoil configuration used at the root section of the wind turbine blade improves the aerodynamic characteristics and overall performance of the wind turbine. Based on a two-dimensional CFD optimization approach, Gaunaa et al. (2012) have quantified the effects of using slats on the thick airfoils of inner part of a modern multi-MW rotor (Bak et al., 2012) to increase power production. The results indicate that slats may be used to boost the aerodynamic performance of the inner part of rotors and, the beneficial effects of using slats may be larger if the slats and the main rotor blade are designed simultaneously. The circular injection slots were explored by Cosoiu et al. (2013); the aim of their study is to optimize the shape of the casing for a small wind turbine; the results showed that the air injected through the slots ensure the control of the main current separation and leads to a slight increase in the volumetric flow rate.

The active flow separation control requires additional energy for the boundary layer control. Among the active methods, the boundary layer suction was initially investigated by Prandtl (1904) but many