2D optimization of a Small Horizontal Axis Wind Turbine blade using flow control techniques

C Papadopoulos\textsuperscript{1,4}, P Kaparos\textsuperscript{1,4}, Z Vlahostergios\textsuperscript{1,2}, D Misirlis\textsuperscript{1,3} and K Yakinthos\textsuperscript{1,4}

\textsuperscript{1}Laboratory of Fluid Mechanics and Turbomachinery, Department of Mechanical Engineering, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece
\textsuperscript{2}Laboratory of Fluid Mechanics and Hydrodynamic machines, Department of Production and Management Engineering, Democritus University of Thrace, 67100, Xanthi, Greece
\textsuperscript{3}Department of Mechanical Engineering, International Hellenic University, Terma Magnesias, 62124 Serres, Greece
\textsuperscript{4}UAV integrated Research Center (UAV-iRC), Center for Interdisciplinary Research and Innovation (CIRI), Aristotle University of Thessaloniki, 57001, Thessaloniki, Greece

kyak@auth.gr

Abstract. In this work, the optimization of the efficiency of a small horizontal axis wind turbine (SHWT) blade segment is presented. Typically, SHWTs have a radius of 1.5 to 3.5 m and a hub height of around 15 m from the ground. SHWTs operate in a relatively small Reynolds numbers range (up to 1.5x10\textsuperscript{6}) and are installed inside the atmospheric boundary layer. This operational environment is characterised by volatile air flow, making the flow over the blade prone to separation. In order to counter this flow behavior, a set of flow control techniques is introduced and studied. These techniques control the flow, either passively, solely by the inclusion of blade add-ons, or actively, by adding energy to the boundary layer. More specifically, two passive flow control techniques and one active flow control technique are modelled and tested on a wind turbine blade segment. The passive techniques implemented in this study are based on the use of vortex generators and tubercles. Vortex generators are small vanes attached vertically to the lifting surface and are widely used in aerospace applications with varying degrees of success. Tubercles, which is a novel flow control technique, are sinusoidal modifications of the blade’s leading edge. The original concept has been inspired from the characteristic flipper of the humpback whale (Megaptera Novaeangliae). Regarding the active flow control technique, a dielectric barrier discharge (DBD) plasma actuator (PA) is used, a technique that adds momentum on the local flow, close to the blade’s surface, by ionizing the air. The impact on the blade aerodynamic efficiency for each technique are evaluated and presented. The results from this evaluation show that flow control techniques can offer a considerable benefit to SHWT by improving the blade’s aerodynamic characteristics, i.e. by increasing the blade lift-to-drag ratio and thus, improving their critical performance efficiency factor.
1. Introduction
Alternative forms of power generation have increasingly replaced hydrocarbons in the last decades. The technology of wind harnessing, holding a third of the renewable energy share, is one of the most important contributors to electricity generators [1]. In 2016 alone, wind turbines were installed that were able to produce more than 54 GW of electricity [2]. The current trend of constantly increasing the hub height and rotor diameter, leads to the exploitation of more and more sites in wind class regions I and II, culminating in offshore wind parks (Figure 1). This usually goes hand in hand with an imbalance between the regions where electricity is consumed and generated. This, in turn, causes increasing investment costs in the electric grid and distribution costs to control the wind-generated electricity. Small wind turbines (SWT) can provide the much-needed distributed electricity. SHWTs, with a mean blade radius of 1 to 2 m, and a capability to produce 1 - 10 kW of electricity, operate in the relatively low Reynolds number regime of 200,000 to 350,000.

The SHWT blade designs still mainly rely on airfoil shapes originally designed for higher Reynolds numbers. Therefore, the characteristics of laminar boundary layers regarding lower frictional losses and higher susceptibility to separations are not considered. This may lead to reported differences between designed and actual SWT power output as much as 10 % [3]. The need of optimization can be fulfilled through the application of flow control techniques, which can be divided to active and passive, depending on whether they need additional energy to be activated.

![Figure 1. A SHWT and a LHWT inside the boundary layer of the earth.](image)

Flow control in wind turbines has seen very little development, mostly restricted in the use of winglets [4]. Therefore, alternative flow control techniques are proposed for this work. An initial approach for the passive flow control over the blade is the vortex generators (VGs). VGs are vanes or small aspect ratio airfoils mounted normally to the lifting surfaces (Figure 2), which locally delay the flow separation and the aerodynamic stalling. They are positioned obliquely to the local airflow to create vortices which draw energy from the fast-moving air away from the airfoil surface and drive them into the near wall region, strengthening the boundary layer. Vortex generators have seen use mostly on aeronautical applications and have been only limitedly implemented in wind turbines. All available literature data refer to a Reynolds number far greater than the one used in the current study (200,000-300,000). This can set a possible trend for lower Reynolds numbers, but is also a challenge, as the effect of these vortex generators is not guaranteed. According to some researchers [5, 6] VGs can have a positive effect in angles of attack greater than 10° for the Reynolds number of 3x10^6. Mueller-Wahl et al. [7] showed that for a Reynolds number of 1x10^6, VGs can increase the efficiency of the airfoil for angles of attack greater...
than 8°. Finally, the work of Wang et al. [8] suggests that VGs can greatly improve the coefficient of lift, even for low angles of attack.

Figure 2. The nature of VGs (a) [7], Tubercles (b) [10] and DBD PA (c) [14] respectively.

Another way to passively control the flow is to use tubercles (TBR), which consists of an array of sinusoidal bumps located at the leading edge of the blade, a concept coming from the humpback whale (Megaptera Novaeangliae) fin. The whale, equipped with tubercles, can achieve high maneuverability, despite their disproportionate size [9]. The basic geometric characteristics of the tubercles, as shown in Figure 2, are the frequency (λ) and the amplitude (A) of the bumps. The lack of literature data concerning the application of tubercles on wind turbines, led the authors to study similar airfoils and suiting Reynolds number conditions. The airfoil NACA 0021 was selected as the reference airfoil as it has seen significant research interest and has similar shape and thickness with the airfoil under study. For a Reynolds number of 120,000 Hansen et al. [10] and Skillen et al. [11], proved that some tubercle designs could increase the efficiency of the blade for an angle of attack (AoA) range of 5°-20°. Malipedi et al. [12] showed that for a Reynolds number of 180,000 tubercles could increase the maximum lift coefficient angle of attack (αCLmax). Additionally, a CFD analysis of Abate and Mavris [13] for tubercles on a SHWT blade showcased some positive potential.

The one and only active flow control technique that will be studied in this work is the Dielectric Barrier Discharge Plasma Actuator (DBD PA). The DBD PA is composed of two electrodes separated by a dielectric material. The one electrode that is exposed to the flow is connected with an AC voltage supply and the other one is the ground electrode. When AC voltage is applied, plasma is produced and the generated ionic wind acts as a body force on the fluid [14]. Seraudie et al. [15] experimentally investigated the effect of a DBD plasma actuator on the laminar to turbulent boundary layer transition on the ONERA-D airfoil by reporting noticeable transition delay. Kurz et al. [16] presented numerical and experimental investigations of controlling boundary layer transition on an ONERA-D airfoil with the use of DBD. The effect of the plasma is modeled with the addition of an eddy-diffusivity expression, an additional source term in the Reynolds-stresses transport equations which is in fact the production of the Reynolds-stresses due to the body force interaction [14, 17].

2. Aim of the study

The aim of this study is to test the ability of three different flow control techniques to improve the aerodynamic efficiency, i.e. the ratio of lift to drag (L/D), of a wind turbine rotor blade segment. The base platform of the wind turbine operates at a tip speed ratio of 5 and has a diameter of 7 m.

The operational Reynolds number region of a SHWT is approximately 200,000 – 450,000, therefore two Reynolds numbers (200,000 and 300,000) were selected for the study, as they resemble the cut-in speed and a mean operating value respectively. Each case was studied for a range of angles of attack from -2° to 10° degrees. The resulting velocity of the air flow in the control volume was 9.74 m/s and 14.61 m/s respectively.

3. Tools and methodology

Before any flow control technique was implemented, the flow over the baseline airfoil was studied. The midspan of the baseline wind turbine blade was identified and selected as the spanwise location with the minimum 3D effects. After the study of the baseline model was over, the flow control techniques were applied on the baseline airfoil.
3.1. Vortex Generators
According to the available literature data, a new average VG setup has been created, in order to be studied. The proposed VG setup will be positioned at 15% of the chord, slightly earlier than the maximum thickness to chord ratio (t/c). This setup has a height H equal to 1% of the chord, maximum distance Z one from the other equal to 5H, total length L equal to 2% of the chord, oblique angle β equal to 18° and a value S equal to 4% of chord (Figures 2 and 3a). In order to consider most of the 3D effects, two sets of VGs were employed on top of the blade segment.

![Vortex Generators](image)
![Tubercles](image)
![DBD PA](image)

**Figure 3.** CAD and implementation of the Vortex Generators (a) Tubercles (b) and the DBD PA (c).

3.2. Tubercles
The lack of literature data concerning the application of tubercles that was mentioned in the introduction confined the geometry characteristics that the tubercles setup could have. Therefore, based on the findings of literature, a mean average was again implemented, resulting in a λ value of 20% of the chord and an amplitude A value of 2% of the chord (Figure 3b).

3.3. Dielectric Barrier Discharge Plasma Actuator
According to the available literature data and the authors experience, an in-house developed methodology [14] was adopted in order to integrate the effect of the DBD plasma actuator in the CFD calculations. Therefore, an additional source term was added in the Reynolds Averaged Navier Stokes equations, which simulated the effect on the flow development of a 30 kV strong current in a pseudo-3D simulation (Figure 3c). This value reflects the in-house experience on DBD plasma actuators and is related to the free stream air velocity.

3.4. CFD calculations
A sufficiently big control volume was used in order to help with the convergence of the complex flow phenomena present in these Reynolds numbers (Figure 4). The control volume of the baseline case was then used for all flow control technique cases. The mesh was constructed in the BETA CAE Systems ANSA mesh generator. The computational grid consisted of less than 1,500,000 nodes and is the product of a 4-mesh grid independency study, until a 2% difference in the C_D value was reached. In this case, 18 inflation layers are implemented, while the first layer thickness was set at 1.6x10^-5m, resulting in a y+ value lower than 1 and thus ensuring that the laminar and transitional boundary layers were accurately captured.

For the CFD calculations, the commercial code Ansys Fluent (ANSYS @ Scientific Research, Release 18.2) is used. Previous numerical studies have shown that the 4-equation SST k-ω turbulence model of Menter [18] could reproduce low Reynolds number experimental data with greater accuracy compared to other turbulence models [19]. Therefore, the 4-equation SST k-ω turbulence model was selected also for this study. Regarding the turbulence parameters, the turbulence intensity at the inlet
boundary was set at 7% and the length scale was set at 0.06 m, values stemming from in-house wind tunnel experiments.

**Figure 4.** The control volume and the mesh quality for the CFD calculations.

### 4. Results

The aim of this study was to test the ability of various flow control techniques to increase the aerodynamic efficiency of a SHWT blade segment with the help of CFD calculations. For the Reynolds number 200,000 case (Figure 5), all flow control techniques showed similar qualitative behaviour for both the coefficient of lift and coefficient of drag. The VG case showed no sign of stall, while the TBR case was the one to stall at the smallest angle of attack. However, the plasma case and the TBR case were the ones with the highest $C_L$ values for the wider range. Regarding the coefficient of drag, again the TBR case and the plasma case showcased significantly lower $C_D$ values than the baseline model. The VG case had a slightly worse efficiency than the baseline model.

**Figure 5.** Lift (a) and drag (b) coefficient comparison for the Reynolds number 200,000 case.

Concerning the Reynolds number 300,000 case (Figure 6), all flow control techniques showed similar qualitative behaviour to the 200,000 case for both the coefficient of lift and coefficient of drag. The TBR case had a greater $C_L$ value than the baseline up to 6° AoA, while the plasma case up to 10° AoA. Again, the $C_D$ values were the smallest for the TBR case and the plasma case. On the other hand, the VG case once more presented the same aerodynamic drag with the baseline model.
Looking at the aerodynamic efficiency (L/D) of the various flow control techniques it can safely be assumed that the plasma case and the TBR case improve the efficiency of the baseline model, at almost the whole AoA range (Figure 7). The VG case presented a similar efficiency as the baseline model. For both Reynolds numbers cases, the L/D ratios of the TBR and the plasma case was almost double than that of the VG and the baseline case.

5. Conclusions

The current study presents an initial numerical analysis of the efficiency optimization of a SHWT blade segment with the application of various passive and active flow control techniques. The results show that the plasma case and the TBR case can significantly increase the aerodynamic efficiency of a wind turbine, by reducing the aerodynamic resistance and at the same time producing more lift. These findings also showcase that both an active and a passive flow control technique could be implemented with the same result on the blade of a SHWT. The possible effects of the added weight, the material selection and the applicability of the studied techniques, needs to be addressed in future studies, as these effects could counterbalance the positive aerodynamic effects. Based on these early results, more variations of the TBR case and plasma case could be exploited in order to optimize the setup.

Acknowledgments

This work has been implemented within the project “ADVENTUS-Advanced Small Wind Turbines” which has been financially supported by the European Regional Development Fund, Partnership
Agreement for the Development Framework (2014-2020), co-funded by Greece and European Union in the framework of OPERATIONAL PROGRAMME: “Competitiveness, Entrepreneurship and Innovation 2014-2020 (EPAnEK)”, Nationwide Action: “Bilateral and Multilateral R&D Cooperations”.

References
[1] Thé J and Yu H A critical review on the simulations of wind turbine aerodynamics focusing on hybrid RANS-LES 2017 methods Energy 138 257-89
[2] Pfaffel S Faulstich and S Rohrig K 2017 Performance and reliability of wind turbines: A review energies 10 1904
[3] Ren Z Jiang Z Skjetne R and Gao Z 2018 Development and application of a simulator for offshore wind turbine blades installation Ocean Engineering 166 380-95
[4] Papadopoulos C Schmid M Kaparos P and Vlahostergios Z 2020 Numerical Analysis and Optimization of a Winglet for a Small Horizontal Wind Turbine Blade Chemical Engineering Transactions 81 1321-26
[5] Miller GE Comparative performance tests on the Mod-2, 2.5-MW wind turbine with and without vortex generators
[6] Gao L Zhang H Liu Y and Han S 2015 Effects of vortex generators on a blunt trailing-edge airfoil for wind turbines Renewable Energy 76 303-11
[7] Mueller-Vahl H Pechlivanoglou G Nayeri and CN Paschereit CO 2012 Vortex generators for wind turbine blades: A combined wind tunnel and wind turbine parametric study Turbo Expo: Power for Land, Sea, and Air 44724 pp 899-914 (American Society of Mechanical Engineers)
[8] Wang H Zhang B Qiu Q and Xu X 2017 Flow control on the NREL S809 wind turbine airfoil using vortex generators Energy 118 1210-21
[9] Aftab SM Razak NA Rafie AM and Ahmad KA 2016 Mimicking the humpback whale: An aerodynamic perspective Progress in Aerospace Sciences 84 48-69.
[10] Hansen KL Kelso RM and Dally BB 2011 Performance variations of leading-edge tubercles for distinct airfoil profiles AIAA J. 49 185-94
[11] Skillen A Revell A Favier J Pinelli A and Piomelli U 2013 Investigation of wing stall delay effect due to an undulating leading edge: An LES study 8th Int. Symposium on Turbulence and Shear Flow Phenomena (Begel House Inc.)
[12] Malipeddi AK Mahmoudnejad N and Hoffmann KA 2012 Numerical analysis of effects of leading-edge protuberances on aircraft wing performance J. of aircraft 49 1336-44
[13] Abate G and Mavriss DN 2017 Cfd analysis of leading edge tubercle effects on wind turbine performance 15th int. energy conversion engineering conf. p. 4626
[14] Vlahostergios Z Kaparos P and Yakinthos K 2019 By-pass transition control with a DBD plasma actuator model coupled with a laminar kinetic energy turbulence model Progress in Computational Fluid Dynamics, an Int. J. 19 137-59
[15] Seraudie A Vermeersch O and Arnal D 2011 DBD Plasma actuator effect on a 2D model laminar boundary layer. Transition delay under ionic wind effect 29th AIAA applied aerodynamics conf. p. 3515
[16] Kurz A Grundmann S Tropea C Forte M Seraudie A Vermeersch O and Arnal D Goldin and R King R 2013 Boundary layer transition control using DBD plasma actuators
[17] Maden I Barckmann K Kriegseis J Jakirlic S Tropea C and Grundmann S 2014 Evaluating force field induced by a plasma actuator using the Reynolds-averaged navier stokes equation 52nd Aerospace Sciences Meeting National Harbor Maryland (AIAA SciTech)
[18] Menter F Langtry R Likki S Suzen Y Huang P and Volker S 2004 A Correlation Based Transition Model Using Local Variables Part 1 - Model Formulation ASME Turbo Expo 4 57–67
[19] Papadopoulos C Kaparos P and Vlahostergios Z and Misiris D 2019 Numerical Analysis and Experimental Measurements of a Small Horizontal Wind Turbine Blade Profile for Low Reynolds Numbers Chemical Engineering Transactions 76 187-92