Applying Spiroid Winglet on The Tip of NREL 5 MW Offshore Wind Turbine's Blade to Investigate Vortex Effects

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Abstract. The present research describes the numerical investigation of the aerodynamics around a wind turbine blade with a winglet using Computational Fluid Dynamics, CFD. In this project our goal is to applying spiroid winglet to examine of the vortex effects on the tip of wind turbine's blade known as "NREL offshore 5-MW baseline wind turbine". At present this method has not yet been implemented in the wind energy sector, in particular because their production still involves excessive costs, compared to the benefits obtainable in terms of wind energy field. A spiroid winglet was investigated with different twist distribution and camber in which pointing towards the suction side (downstream). The comparisons have been done between two operating conditions in terms of pressure, thrust, torque, relative velocity, streamlines, vorticity and then mechanical power.

1 Introduction

With the shortage of the fossil fuels and the increase of environmental awareness, environmentally friendly and renewable sources of energy have become increasingly important nowadays. Among renewable clean energy sources, wind turbine is attributed as the least contributor to the environment destruction. The rapid potential growth of wind turbine throughout the world both offshore and onshore, the demand and it's invaluable features make it appropriate and lucrative research topic, particularly to develop its performance. According to data provided by the Renewables Global Status Report in 2019, the global wind market was roughly about 51 GW added in 2018, boosting cumulative capacity 9% to 591 GW [1].

There has been a great deal of research investigating the effects of adding winglets to plane wings, however there is less studies considering the potential benefits of adding winglets to a rotor. Van Bussel [2] applied momentum theory to investigate HAWT winglets, and also carried out a significant amount of experimental work. He explains the power increase to be from the downstream shift of the wake vorticity. Imamura et al. [3] used a free-wake vortex-lattice code to investigate the aerodynamic effects of winglets on wind turbines. Johansen [4] carried out Navier-Stokes based simulations using the CFD code EllipSys3D, and suggests that the shift in vorticity alone cannot account for the power gains from the winglet, the reduction of tip effects being the distinguished feature. Reduction in tip effects here means a reduction in span-wise flow and a diffusing effect on the tip vortex, this can lead to a reduction in downwash on the main blade and so reduced induced drag, increasing power

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production. Taborda et al. [5] analyzed a cross-flow vertical axis wind turbine based on 3D transient turbulent simulations using the Transitional SST model. The original rotor without winglet, with an asymmetric winglet and with a symmetric winglet was analyzed. They came to the conclusion, that the performance can be increased using winglets, the optimal solution being to use a symmetric winglet. Berlferhat et al. experimentally analyzed the polar for different winglets [6]. The aerodynamic efficiency of HAWTs with blade tip modifications was also discussed in the work of Gaunaa and Johansen [7].

As a result of the pressure difference, an airflow is induced from the higher pressure side to the suction side along the end of the blade and a wingtip vortex is generated, which results in losses. In wind turbines with small aspect ratio these losses can be large (even up to 25%; [8]), while at high aspect ratio corresponding losses become negligible. As shown in the study of Gosselin et al., the last 20-30% of the blade height is less effective [9]. Amet also came to a similar conclusion, with 22% loss of performance due to the tip vortices and blade/arm junctions [10], while Qin et al. reported 40% losses compared to 2D simulations [11]. This aerodynamic problem has been known for a long time, mostly in connection with airplanes, and several blade tip modifications were already proposed to overcome it, e.g., vortex diffuser, tip sails [12], wing-grids, raked tip [13] and many different winglet designs. Winglets are now widely used for airplane wings [14] and, to a less extent, for wind turbines.

It is obvious that more should be done to design an optimum blade characterizing winglets, therefore there are different methods for simulating the aerodynamics of a wind turbine depending on levels of intricacy and accuracy, such as the Blade Element Momentum (BEM) theory and solving the Navier-Stokes equations using Computational Fluid Dynamics (CFD).

In this study a 5 MW NREL rotor blade has been simulated as a baseline and also again by adding a spiroid winglet on the tip of blade with a diameter about 126 m.

Fig. 1. 3D model of blade a) spiroid winglet b) baseline

2 Methodology

Computations are made by using Open-Foam with general purpose incompressible Navier-Stokes solver. The flow is assumed steady state and turbulence is modeled by $k - \epsilon$ model with wind speed 11.4 m/s and rotational speed and pitch angle at wind speed are kept constant. The vortex effect at tip of the blade has been compared in two conditions with baseline and with spiroid winglet, both have studied in the same circumstances. The domain for this study has been selected in one third of the cylindrical shape with 7R length and around 3R height. The mesh is generated using Snappy Hex Mesh (SHM) in Open-Foam with total cells around 10 million.

Fig. 2. Cross section of the blade 30m in the specified domain

According to fig.2 the mesh cells, concentrated in greater numbers in the areas near the blade geometry and lower one in the rest of the domain for the sake of better optimization. As we can see from the figure of the incoming and outgoing meshes, the control volume has been further increased by twice the radius, thus reaching a value of around 185 meters. In the Open-Foam calculation code, the internal control volume is the rotating part, while the external part is the fixed part. This mode of study is called MRF (Multiple Reference Frame), is a model through which we study domains that move at different rates of rotation. During the calculation, the rotating part remains fixed in a specific position and the flow field at that moment is observed, and continuity conditions are used in the areas of interface with the

fixed part. According to the NREL 5 MW off-shore wind turbine data sheet analysis have been done in two separated parts for two types of blades before rated power in 2.6 MW and after rated power 5 MW that will be constant after reaching to the rated power. The reason is that the optimum performance will occur in the range between initial power and rated power.

Table 1. Aerodynamic Parameters

	Velocity (m/s)	Rotor Torque (kN.m)	Rotor Speed (rad/s)
Before rated power	9	2500	1.047
After rated power	11.4	4200	1.257

Table 2. Aerodynamic and Turbulence Characteristics

Density of the air ρ (kg/m ³)	1.225
Dynamic viscosity of air at 15 [°] C	1.8E-5
Kinematic viscosity of air at 15 [°] C (m ² /s)	1.47E-5
Turbulent length l (m)	30
Turbulence intensity (I)	0.05
Turbulence kinetic energy (k)	0.48735
Turbulence dissipation rate (ϵ)	0.00186347
Turbulence viscosity (ν)	11.47

3 Result and Discussion

The pressure is distributed in a non-homogeneous way on the blades surface, we have two sections in which are known as pressure side with higher value of pressure and another side is suction side with lower value of pressure this difference is responsible for generating lift and torque. Also at the tip of both blades we have more concentration of pressure. The distributed pressure increases by moving from root of the blade to the tip of the blade. Also the range of the distributed pressure is a bit higher for the blade with winglet. In all of the pictures as it can be seen the upper surface of the airfoil is suction side with lower concentration of pressure and the lower surface is the pressure side with higher concentration of pressure. In the following pictures it will show the distributed pressure in sections at 30% of the blade’s length and on the tip of blade around these selected airfoils.

Fig. 3. Distributed pressure at 30%R a) winglet b) baseline

Fig. 4. Distributed pressure on the tip of blade 62m a) winglet b) baseline

The distributed section axial force and section torque are obtained in several cross sections of the blade and then by taking integrate from variables in each cross sections. We can see that the ranges of the distributed section axial force and section torque for the blade with winglet is a bit more than the baseline and also the F_y and the moment in winglet state are higher than the baseline.

Fig. 5. Distributed section axial force a) before and b) after rated power respectively

Fig. 6. Distributed section torque a) before and b) after rated power respectively

According to the above figures it is clear that applying spiroid winglet has better performance compared in baseline configuration. The rotation for the baseline and for the winglet is in the y axis therefore for calculating the power we should compute torque at the rotational axis. So the total power can be computed as follow for each blades.

$$P_b = 3 \cdot \Omega \cdot T_y \tag{1}$$

$$P_w = 3 \cdot \Omega \cdot T_y \tag{2}$$

Fig. 7. Distributed power a) before and b) after rated power

The wake vortex structure is one of the important indexes in the aerodynamic analysis of the turbine. The wake vortex near the blades has great influence on the aerodynamic properties of the blades, while the wake vortex further from the blades may influence the aerodynamic performance of other turbines behind. The vorticity trace has been represented in three sections near the tip of the blade to comparing the vortex effect at the tip of each blade so:

Fig. 8. Distributed vorticity at 0.5m from the lateral side of the blade a) winglet b) baseline

Fig. 9. Distributed vorticity at 3m from the lateral side of the blade a) winglet b) baseline

Fig. 10. Distributed vorticity at 6m from the lateral side of the blade a) winglet b) baseline

Fig. 11. Vorticity trace around the blade in radial direction in predefined domain a) before and b) after rated power

Fig. 12. Vorticity trace around the blade in lateral direction in predefined domain a) before and b) after rated power

The Fig.11 is vorticity around the blade in several cross sections in radial direction in domain while Fig.12 represent the vorticity in lateral state from distance 0.5m up to 7m from the blade. According to the pictures in each scenario and plots we can found that the vorticity effect in each section of the blade in our domain for the winglet is a bit less than baseline but in lateral from distance of 0.5 up to 7 meters the total vorticity trace along the blade for the winglet is more higher than the baseline. Also typically at the tip of blade the vorticity for the winglet is higher than the baseline.

$$r = \sqrt{coordx^2 + coordz^2} \quad (3)$$

4 CONCLUSION

In this paper, the aerodynamic performance of the NREL offshore 5-MW wind turbine under two different design baseline and spiroidal winglet were simulated with Open-FOAM. And the rotor thrust, torque, power and wake vortex aerodynamic data and flow field information were obtained in detail. By analyzing the results we can obtain that applying winglet can be useful in compare to the baseline case. In general the device produce a higher vorticity. The purpose to control the detrimental tip effect, the device seems to do not give a good effect in terms of vorticity. This can be explained by considering that probably the pitch angle used

was not the optimal for this design in these conditions. Anyway, in this specific application, we noticed an increase of power and performance of the blade with the winglet. To understand this effect, further studies are needed. Some questions are still open, which will be the subject of the upcoming research.

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