Numerical Analysis of Winglets on Wind Turbine Blades using CFD

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Summary

The present paper describes the numerical investigation of the aerodynamics around a wind turbine rotor with winglets using Computational Fluid Dynamics, CFD. A parameter study is carried out where four of the key parameters describing a winglet are varied and the various effects are analyzed based on resulting mechanical power and thrust.

Results show that adding a winglet to an existing wind turbine rotor increases produced power of around 1.0 % to 2.8 %. The additional increase in thrust is around 1.2 % to 3.6 %.

Introduction

The main purpose of adding a winglet to a wind turbine rotor is to decrease the total drag from the blades and thereby increase the aerodynamic efficiency of the turbine. Reduction of total drag is obtained if the additional drag from the winglet is less than the reduction of the induced drag on the remaining blade.

The art is then to design a winglet, which optimizes drag reduction, maximizes power production and minimizes thrust increase.

The resulting pressure difference on an operating wind turbine blade causes inward spanwise flow on the suction side and outward spanwise flow on the pressure side near the tip. At the trailing edge, vorticity is generated, which is the origin of induced drag.

A winglet is a load carrying device that reduces the spanwise flow, diffuses and moves the tip vortex away from the rotor plane reducing the downwash and thereby the induced drag on the blade.

Method

Six key parameters describe the shape of a winglet,

Figure 1. These include

- winglet height
- sweep angle
- cant angle
- curvature radius
- toe angle
- twist angle

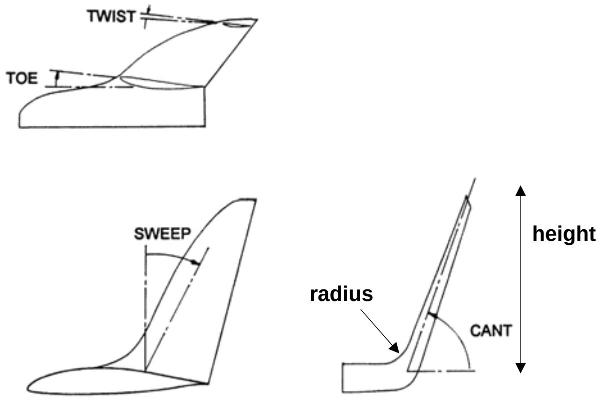

Figure 1: Definition of key parameters describing the winglet. (From ref. [1])

In the present work only winglet height, curvature radius, sweep and twist are investigated. Additionally, the effect of bending the winglet either upstream or downstream will have an effect. Based on previous studies, ref. [2] only winglets bended towards the suctions side have been analyzed in the present work. Also, the local airfoil shape and taper is not accounted for.

Several winglets have been designed and analyzed based on increase in produced power and thrust compared to the original rotor without winglets. Based on the results of the initial winglet design each of the parameters have been varied for obtaining the most efficient winglet configuration. The resulting design matrix is given in Table 1.

Table 1: Overview of the winglets investigated.

Winglet name	Winglet height [% radius]	Curvature radius [% winglet height]	Sweep angle [º]	Twist angle [º]
W1	**2%**	**50%**	**0**	**0.0**
W2	**2%**	**50%**	**0**	**2.0**
W3	**2%**	**50%**	**0**	**4.0**
W4	**2%**	**50%**	**0**	**8.0**
W5	**2%**	**100%**	**0**	**0.0**
W6	**2%**	**100%**	**0**	**4.0**
W7	**2%**	**25%**	**0**	**4.0**
W8	**2%**	**25%**	**30**	**4.0**
W9	**4%**	**12.5%**	**0**	**4.0**
W10	**1%**	**50%**	**0**	**4.0**

The first four set of computations were made on winglets of height = 2 % rotor radius, a curvature radius of 50 % winglet height, no sweep and with different twist angles at the tip of the winglet. They have been denoted W1, W2, W3 and W4, respectively. Based on the results from these, two winglets were designed with a curvature of 100 % winglet height and the twist of W1 (0.0°) and W3 (4.0°). They are denoted W5 and W6, respectively.

Following, the most efficient twist distribution (twist = 4.0º) was investigated with a curvature radius of 25 % of winglet height. This winglet is denoted W7. Since W7 resulted in the highest increase in power production, the effect of sweep was based on W7 having a sweep angle of 30º and denoted W8.

Finally, the effect of the height of the winglet was investigated based on the configuration of W7, now having a winglet height of 4 % and 1 % rotor radius, respectively. These winglets are denoted as W9 and W10.

For clarity, some of the individual winglets are shown in the following figures.

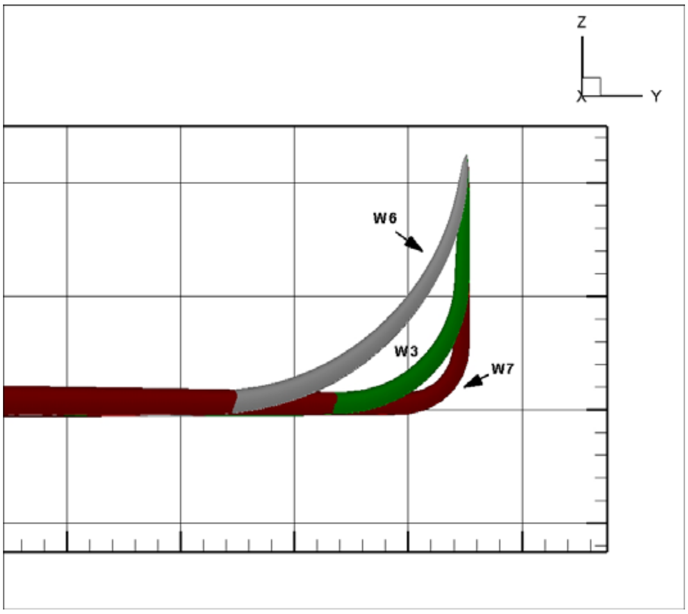

Figure 2: Winglets with different curvature radius.

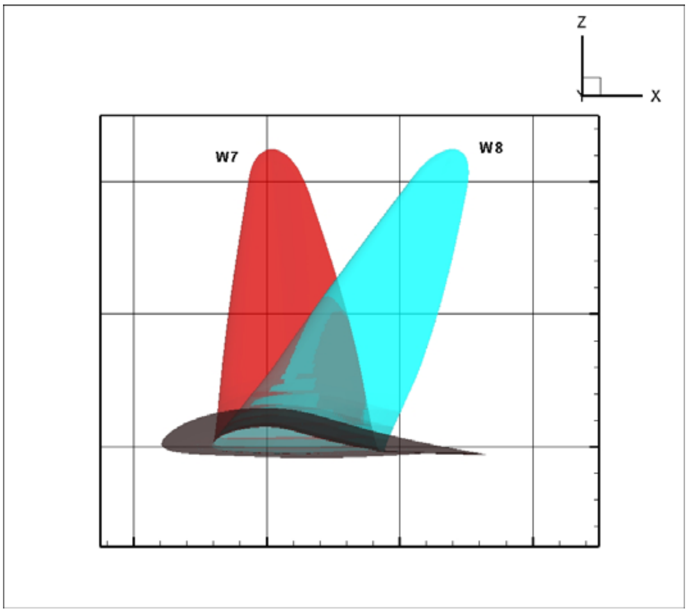

Figure 3: Winglets with different sweep angle.

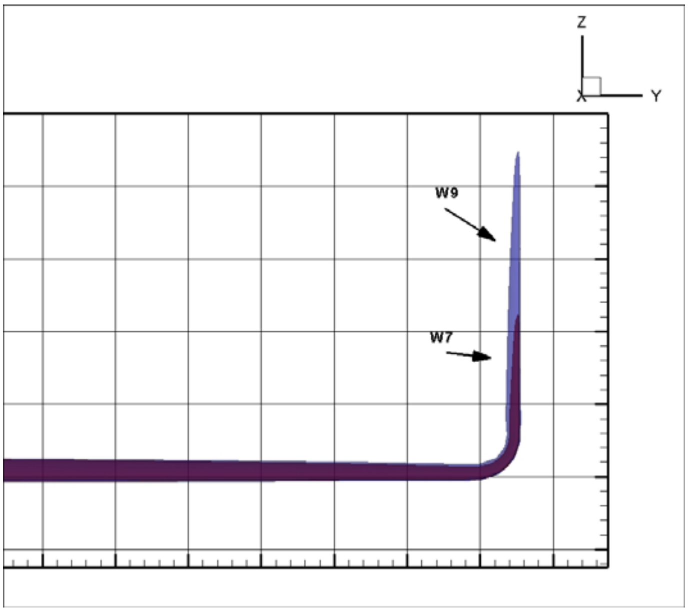

Figure 4: Winglets with different winglet height.

The way the winglets are designed is by manipulating the outer 10% of the original wind turbine blade. The outer part of the blade is simply stretched linearly in the spanwise direction corresponding to the winglet height and subsequently bended towards to suction side with a given curvature radius, sweep and twist. Using this method the wetted area of the different resulting blades is not equal, since the curve length are different. See Figure 5. This has to be taking into account analyzing the results.

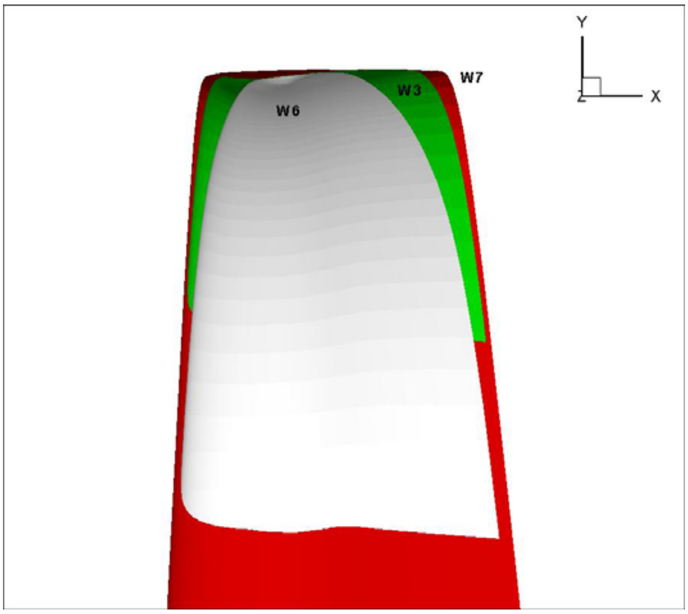

Figure 5: Different winglets result in different wetted area.

Computations are made using the Risø/DTU general purpose incompressible Navier-Stokes solver, EllipSys3D[3],[4] and[5]. The third order accurate QUICK scheme is used for computing the convective terms and pressure correction is computed using the SIMPLE algorithm. All computations are performed assuming steady state conditions with a moving mesh technique based on analytical prescribed rotation, ref. [6]. The inflow is uniform with low turbulence intensity and turbulence is modelled using the k-ω SST model [7]. Computations are performed assuming a rotor only configuration where the tower and the nacelle are neglected.

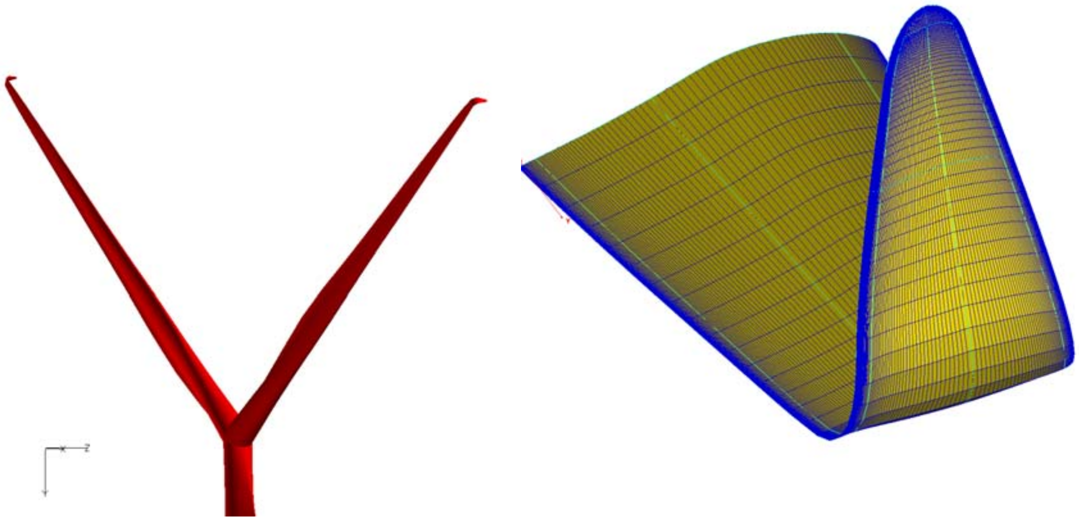

Figure 6: Rotor only configuration (left) and surface mesh around the winglet (right).

The surface mesh is generated using Gridgen**,** a commercial mesh generator developed by Pointwise, Inc. and consists of 132 blocks of 32^2 cells for the entire rotor. The volume mesh is generated using Risøs in-house grid generator HypGrid[8] and away from the surface 128 cells are used resulting in $17.3 \cdot 10^6$ cells in total. No-slip is assumed on the entire geometry. The outer boundary of the computational domain is placed approximately six rotor diameters away.

Results

The original rotor is a MW-size wind turbine. Only one wind speed, W = 8 m/s is computed which corresponds approximately to maximum power coefficient, C_P. The mechanical power and thrust computed are shown in Table 2 together with the increase compared to the original rotor without winglets.

Table 2: Resulting mechanical power and thrust and the increase compared to the original blade.

	Mech. Power	**Increase %**	**Thrust**	**Increase %**
Original rotor	**989.0**	**-**	**211.3**	**-**
W1	**1005.0**	**1.62**	**215.3**	**1.89**
W2	**1005.0**	**1.62**	**215.4**	**1.94**
W3	**1005.0**	**1.62**	**215.4**	**1.94**
W4	**1004.5**	**1.57**	**215.5**	**1.99**
W5	**1000.7**	**1.18**	**214.3**	**1.42**
W6	**1000.7**	**1.18**	**214.5**	**1.51**
W7	**1006.2**	**1.74**	**215.8**	**2.13**
W8	**1003.2**	**1.44**	**215.7**	**2.08**
W9	**1016.4**	**2.77**	**218.8**	**3.55**
W10	**998.7**	**0.98**	**213.8**	**1.18**

The first four winglets all have an increase in power around 1.6 % and an increase in thrust around 1.9 %. There is hardly any difference due to the difference in twist. Investigating winglets with larger curvature radius, W5 and W6, with twist = 0.0° and 4.0°, respectively, again hardly any difference with respect to twist was seen. However, having a twist of 4.0° did have a minimal increase compared to 0.0°, leading to the choice of having twist = 4.0° for the remaining studies. A larger curvature resulted in smaller increase in power. Therefore a curvature radius of 25 % of winglet height was designed, W7. This resulted in an even higher increase in power (1.7 %) but also in thrust (2.1 %).

W8 was designed with a positive sweep of 30° keeping other parameters as W7. However, power and thrust showed less increase compared to W7.

Finally, the height of the winglet was investigated. W9 has twice the winglet height and W10 has half the winglet height as W7. The largest winglet, W9, showed the largest increase in both power and thrust, but the design resulted in a very slender winglet with a large aspect ratio. This does not seem as a feasible design since the loads on the winglet is quite high.

Discussion

In general, results show that adding a winglet to the existing blade can change the downwash distribution leading to increased produced power, but a load analysis is necessary to verify whether the increased thrust can be accepted. In general the following can be stated:

- Mechanical power and thrust increases as curvature radius decreases
- Sweeping the winglet 30° backwards does not increase mechanical power.
- Mechanical power and thrust increases as winglet height increases
- Only small dependence on winglet tip twist is seen.
- The effect of toe angle has not been investigated here but might have a positive effect on the produced power.

Finally, it should be mentioned that tip noise can possibly be affected by a winglet. This has not benn investigated in the present work.

Acknowledgement

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