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Numerical Study on Performance of Curved Wind Turbine Blade for Loads Reduction

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1 INTRODUCTION

Nowadays, the wind turbines are becoming larger and larger. This is mainly due to the fact that the power is increasing with the rotor area. At the same time, however, the weight is increasing and so, the cost. Technological innovation is fundamental in this development to keep the cost low while the size of the turbines is increasing.
The crucial step is to keep the loads low. Several solutions are in development. The present work is focused on a numerical investigation about the performances of swept-blade wind turbine rotors.
There is an increased interest in the study of swept-blade wind turbine rotors in order to increase energy capture without an increase in the turbine loads; at the same time, a swept-blade geometry is less sensitive to wind gusts and so, more tolerant for fatigue loads. A code developed at ECN, based on the generalized lifting line theory and coupled with a free wake method, was used. The code has been extended in order to take into account the deformation of the blade due to torsion and bending moments. In the next paragraph, the code is presented. Then, the results of parametric analyses are illustrated and discussed. This research is also including analyses in extreme gusts conditions and considerations about performances and noise.

2 NUMERICAL MODEL

2.1 *The numerical code AWSM*

A code, named AWSM, based on generalized lifting line theory in combination with a free vortex wake method has been developed at ECN (van Garrel, 2003). The main assumption in the lifting line theory is that the extension of the geometry in span-wise direction is predominant compared to the ones in chord and thickness direction; because of this, the real geometry is represented by a line passing through the quarter chord point of each cross section and all the flow field in chord-wise direction is concentrated in that point.
Considering the elementary force (*dF*) generated by the geometry, this can be calculated by using the three-dimensional form of the Kutta-Jukowsky equation (eq. 1).

$$d\vec{F} = \rho\Gamma\vec{V}\times d\vec{l} \qquad (1)$$

It should be noted that *dF* can also be calculated if the section values of lift coefficient C_l and angle of attack α are known (eq. 2).

$$\left|d\overline{F}_i\right| = \frac{1}{2}\rho V_\infty^2 C_{Li}(\alpha_i)dS_i \qquad (2)$$

Combining equations (1) and (2), gives us

$$\left|d\overline{F}_i\right| = \left|\rho\Gamma_i(\overline{V}_\infty + \sum_{j=1}^{N}\frac{\Gamma_i}{c_{ij}}\overline{v}_{ij}) \times d\overline{l}_i\right| = \frac{1}{2}\rho V_\infty^2 C_{Li}(\alpha_i) dS_i \tag{3}$$

The complete formulation can be found in van Garrel, 2003 and validation tests are presented in Grasso et al., 2010. Here, it should be noticed that the effects of viscosity are taken into account through the user-supplied nonlinear relationship between local flow direction and local lift, drag and pitching moment coefficients and that an iterative generalized scheme is implemented to reach the convergence.

Because of the formulation, very general shapes can be prescribed and investigated, in particular, curved blades. Then, because the iterative scheme is time dependent, changes in the shape of the geometries can be prescribed.

2.2 *Geometrical deformations*

To analyze the effects due to the bending and torsion motions acting on the blade, a simplified model is used (Stoddard, Egglestone, 1987). According to this model, the complex tapered beam is represented by a simple hinged, cantilevered beam with a spring at the hinge.

The hinge-spring model allows for three directions of blade motion: flapwise bending, chordwise bending and torsion. In the following development the in plane motion (chordwise direction) is neglected. Only the first bending mode is considered. The fourth-order Runge-Kutta method was used to solve both the equations.

2.2.1 *Out of plane bending*

In order to consider the effects of bending due to the out-of -plane motion, the equivalent beam has a hinge of stiffness K_β at offset eR from the root.

Neglecting the effects due to the yaw rate and crosswind, the flapping equation of motion is (eq.4)

$$I_\beta\ddot{\beta} + \beta[\Omega^2(I_\beta + eRS_\beta) + K_\beta] = M_\beta \tag{4}$$

Where

$$I_\beta = \int_{eR}^{R} m(r)(r - eR) \tag{5}$$

$$K_\beta = (2\pi\omega_{NR})^2 I_\beta \tag{6}$$

The “e” parameter is defining the location of the hinge along the blade. It is calculated by using an iterative process in which the Southwell coefficient is calculated and, from that, “e” is determined.

M_β is the flapping moment due to the aerodynamic forces calculated taking into account the contribution of flapping velocity ($r\dot{\beta}$) to the axial component of wind velocity.

The effect due to the presence of this velocity is a damping contribution to the motion of the beam.

2.2.2 *Torsion*

In order to consider the effects due to the torsion motion, the equivalent beam has a torsion spring of stiffness K_θ at root. This means that the angular displacement is constant along the blade. The torsion equation of motion is (eq.7).

$$I_\theta \ddot{\theta} + b\dot{\theta} + K_\theta \theta = M_\theta \quad (7)$$

Where

$$I_\theta = I_G + Md^2$$

$$b = \varsigma(2\sqrt{K_\theta I_\theta})$$

$$K_\theta = (2\pi\Omega)^2 I_\theta$$

I_G is the barycentric mass moment of inertia.
Md^2 is the transport moment. It is calculated when the axis of the beam is different from the pitch axis.
ξ is the damping factor.
M_θ is the torsion moment due to aerodynamic moment and forces.

3 NUMERICAL ANALYSES

Three different swept blade models have been used for this parametric analysis (figure 1). The reference geometry is the Reference Wind Turbine (RWT) of the European project Upwind.

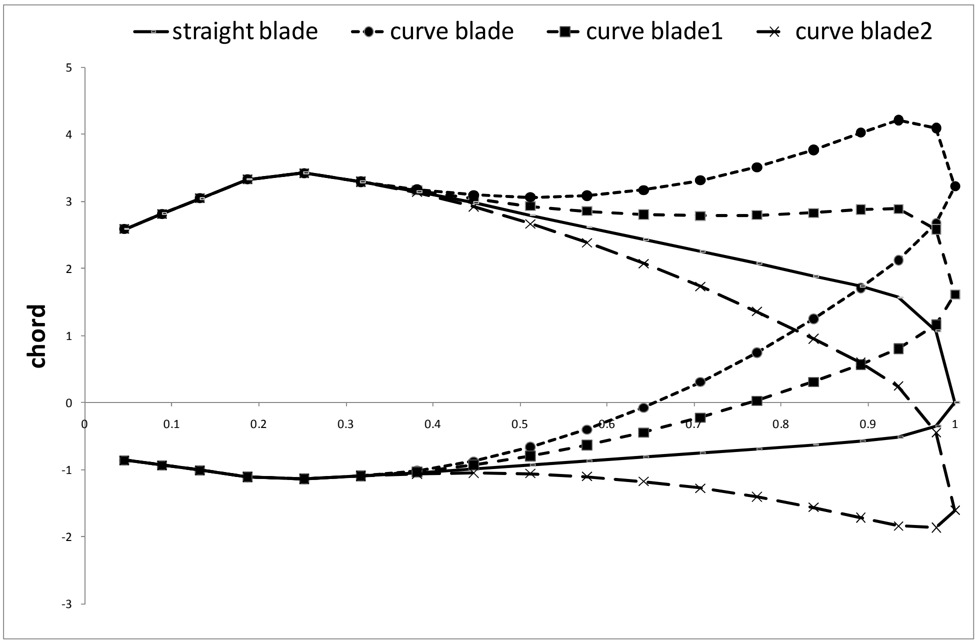

Figure 1 Blade geometries used during the parametric analysis.

Table 1 Main characteristics of the geometries used for the parametric analysis.

Blade ID	description
Curve blade	Aft swept blade, sweep at the tip: 3.22 m.
Curve blade1	Aft swept blade, sweep at the tip: 1.611 m.
Curve blade2	Fore swept blade, sweep at the tip: -1.611 m.

3.1 *Uniform conditions*

In order to consider the effects, due to the use of a swept blade on wind turbine performance, the lift distribution for the blade models, has been compared. The lift distribution was obtained by considering for the wind turbine a wind speed of 8 m/s, rotational speed 0.964 rad/s and a simulation time of 97.77s that represents the needed time to have stable flow. The simulation was performed by allowing the shed vortices to roll up through wake self influence. In figure 2, the lift distribution is shown. By using an aft swept blade, the loads on the blade decrease; as consequence, a power loss of 10% for the *curve blade* and of 3% for the *curve blade1* is obtained. Using the fore swept blade (*curve blade2*) can be seen an increment of loads and thrust. This leads to an increase in tower loads, requiring a stiffer and more expensive structure.

Table 2 Wind turbine performances referred to the reference geometry.

	Power [kW]	ΔPower (%)	Thrust [kN]	ΔThrust (%)
Straight blade	1890.1	/	367.9	/
Curve blade	1700.5	-10.1	292.3	-20.6
Curve blade 1	1830.3	-3.2	324.5	-11.8
Curve blade 2	1930.4	2.1	424.7	15.4

3.2 *Gust conditions*

The same tests were carried out in presence of a gust, modeled according to the international standard IEC 61400-1. A wind speed of 11m/s and a rotational speed of 1.246 rad/s have been used for this simulation. Figure 3 shows the comparison in terms of time evolution of loads at 92% blade radius. Because of the gust, the lift coefficient and the angle of attack are changing, following the gust evolution. In Table 3, the lift coefficient percentage variations, referred to the straight blade are illustrated. By adopting an aft-swept blade, a significant reduction in load fluctuation and so in fatigue, can be achieved.

Table 3 Change in lift coefficient during the gust, referred to the value for the reference geometry.

	ΔCl (%)
Straight blade	/
Curve blade	-17.4
Curve blade 1	-9.8
Curve blade 2	2.8

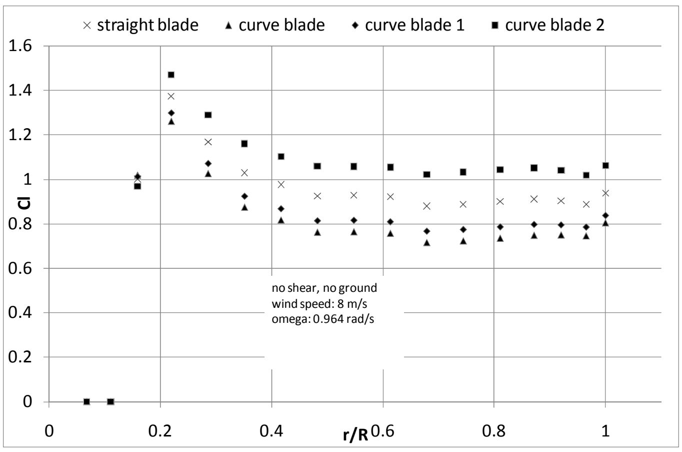

Figure 2 Lift coefficient distribution along the blade. Comparison between the geometries.

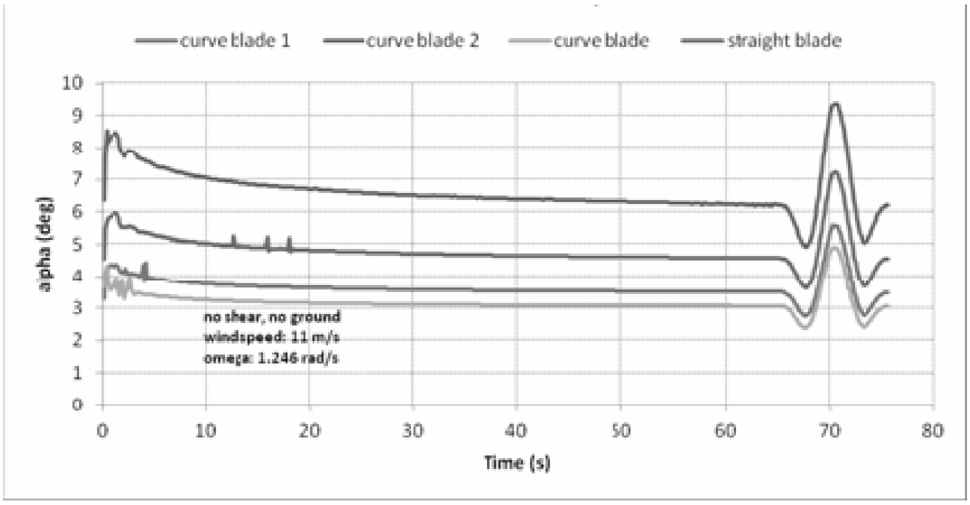

Figure 3 Time evolution of local angle of attack at 92% of the blade.

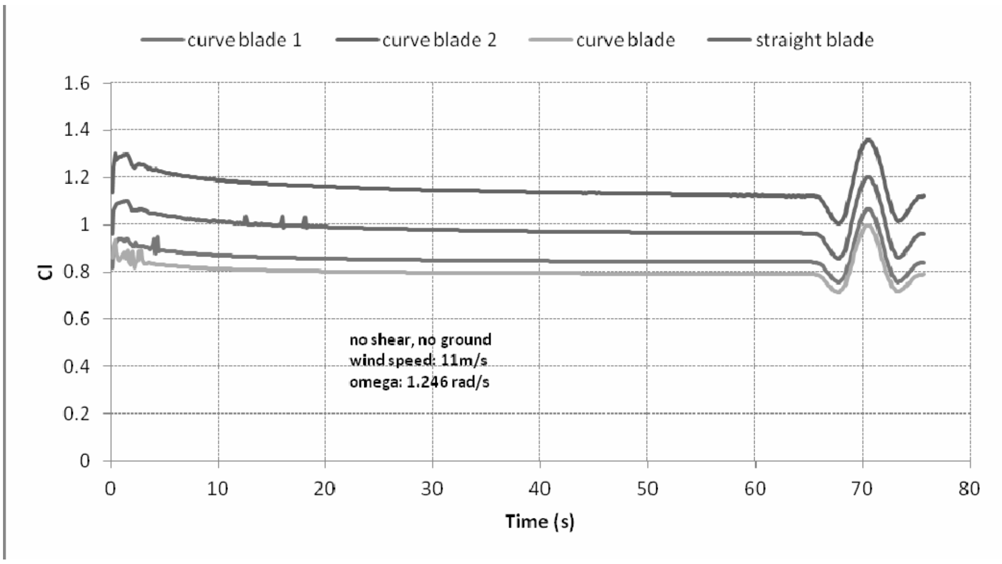

Figure 4 Time evolution of local lift coefficient at 92% of the blade.

3.3 *Noise prediction*

Part of the present work has been focused on the noise produced by the geometries. A numerical code, named Silant, developed at ECN was used for these analyses (Boorsma, Bulder, 2010). The noise sources that are taken into account are trailing edge, inflow and tip noise, using the models of Brooks, Pope and Marcolini, 1989 (BPM) and Amiet, 1975 and Lowson, 1992. The blade is divided into a number of independent elements for which effective inflow velocity and angle of attack information is a necessary input. A distinction is made between the various profiles along the blade span by including their boundary layer displacement thicknesses at the trailing edge, calculated by using RFOIL (van Rooij, 1996).
The "A-weighted" noise is considered.

Table 4 noise contributions for the different blades.

	Inflow noise [dB]	Trailing edge noise [dB]	Tip noise [dB]
Straight blade	87.76	95.78	82.2
Curve blade	87.79	95.55	79.89
Curve blade 1	87.78	95.6	80.56
Curve blade 2	87.73	95.18	83.95

Looking at the results in table4, the differences in terms of inflow noise are very small. This is due to the fact that the inflow noise is mainly dependent from the external conditions. Because the different blades are working in the same atmospheric conditions, no sensitive differences are found.

The differences are instead visible in tip noise contribution. This is consistent with the expectations because the curvature of the blade at the tip modifies the local aerodynamic characteristics at the tip in terms not only of loads but also vortices.

Differences were also expected for the trailing edge noise, but the values are very close with each other. This may be due to several reasons. The trailing edge noise is mainly dependent on the shape of the airfoils and on the boundary layer properties at the trailing edge. The noise calculation are performed in uniform conditions (see previous section); in these condition, AWSM is predicting a local angle of attack very small and also the differences between the geometries are around one degree, so the boundary layer characteristics are not changing sensibly. On the other hand, it should be kept in mind that the presented results are affected by the implemented model for the deformation. According to this model, the torsion is concentrated to the root and all the sections are deforming with the same angle. This means that in reality the torsion along the blade can be larger and so give larger contribution to the noise. However, further investigation are in schedule to address this point.

4 CONCLUSIONS

In order to investigate the performances of aft-swept blades, a code based on the lifting line theory and coupled with a free wake method has been used. The code has been extended in order to take into account the dynamic deformation of the geometry due to the aerodynamic forces acting on the blades. A first parametric investigation has been performed by comparing the performances of blades with different curvatures. The results are consistent with the expectations and show that aft-swept blades have beneficial effects to reduce loads and fluctuations, even if with a reduction in power production. On the other hand, fore-swept blades show an increase in load and so, an increase in thrust.

Analyses on noise, show that the tip noise can be reducing by adopting a swept blade.

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