Numerical Study on Performance of Innovative Wind Turbine Blade for Load Reduction

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Abstract

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. The present work is focused on a numerical investigation about the performances of swept-blade wind turbine rotors. A code developed at Energy Centre of the Netherlands, 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. After the code is presented and the extensions are explained, a parametric analysis is performed on different blade shapes and then, the results are illustrated and discussed.

Nomenclature

α = angle of attack [deg]
α_i = local angle of attack for wing section i [deg]
c = chord [m]
c_j = chord for wing section j [m]
C_l = local lift coefficient [-]
dF = differential aerodynamic force vector [N]
dl = directed differential vortex length vector [m]
dS_i = differential planform area at control point i [m^2]
e = non dimensional hinge offset of equivalent beam
Γ = vortex strength in the direction of r_0 [$m^2\ s^{-1}$]
I_b = mass moment of inertia of equivalent beam [$Kg\ m^2$]
I_G = barycentric mass moment of inertia [$Kg\ m^2$]
L = lift [N]
r_0 = vector from beginning to end of vortex segment [m]
r_1 = vector from beginning of vortex segment to arbitrary point in space [m]
r_2 = vector from end of vortex segment to arbitrary point in space [m]
ρ = fluid density [$kg\ m^{-3}$]
u_{ai} = unit vector at control point i in chord-wise direction [-]
u_{ni} = unit vector at control point i in normal to chord direction [-]
V = local fluid velocity [$m\ s^{-1}$]
V_∞ = velocity of the uniform flow or free stream [$m\ s^{-1}$]
v_{ij} = non dimensional velocity induced at control point j by vortex i , having a unit strength [-]
ω_{NR} = non rotating natural frequency of the blade [$rad\ s^{-1}$]

I. Introduction

There is an increased interest in the study of innovative shapes for wind turbine rotors, in order to increase energy capture without an increase in the turbine loads. Reduce loads and load fluctuations helps to reduce fatigue problems and, more in general, structural problems. From economic point of view, this means to have the opportunity to decrease the costs connected to materials and manufacturing, especially for the rotor, but also for other components like the tower.

One of the possible solutions is the development of aft-swept blades. Because of geometry, the blade produces by itself a torsion that should reduce the local angle of attack and so, the loads. For this mechanism, a swept-blade geometry is also expected to be less sensitive to wind gusts and so, more tolerant for fatigue loads.

The present work is focused on a numerical investigation about the performances of swept-blade wind turbine rotors. A code developed at Energy Centre of the Netherlands (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.

II. Aerodynamic Wind-turbine Simulation Module

The Aerodynamic Wind turbine Simulation Module (AWSM) was developed at ECN by van Garrel [1]. It is based on generalized lifting line theory in combination with a free wake method. The main assumption in this 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).

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

For each point along the lifting line, the local velocity V_i can be calculated as superimposition of the local free stream velocity and the local induced velocity (eq. 2) where v_{ij} is the dimensionless induced velocity calculated from Biot-Savart formula (eq. 3).

$$V_i = V_\infty + \sum_{j=1}^{N}\frac{\Gamma_j v_{ij}}{c_j} \qquad (2)$$

$$\overline{v_{ij}} = \frac{-1}{4\pi}\int\Gamma\frac{\bar{r}\times d\bar{l}}{r^3} \qquad (3)$$

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. 4).

$$\left|d\bar{F}_i\right| = \frac{1}{2}\rho V_\infty^2 C_{Li}(\alpha_i)dS_i \qquad (4)$$

Combining equations (1) and (4), gives us

$$\left|d\bar{F}_i\right| = \left|\rho\Gamma_i(\bar{V}_\infty + \sum_{j=1}^{N}\frac{\Gamma_i}{c_{ij}}\bar{v}_{ij})\times d\bar{l}_i\right| = \frac{1}{2}\rho V_\infty^2 C_{Li}(\alpha_i)dS_i \qquad (5)$$

Where:

$$\alpha_i = \tan^{-1}\left(\frac{\overline{V}_i \cdot \overline{u}_{ni}}{\overline{V}_i \cdot \overline{u}_{ai}}\right) \quad (6)$$

In AWSM, 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; this means that equation 4 can be numerically solved minimizing the difference between the elementary force obtained from sectional properties and the one calculated from the Kutta-Jukowsky formula.

Because of the generalized formulation, the shape of the lifting line can be very general (i.e. winglets, curved blades) and also multi-body configurations can be investigated. Then, because the iterative scheme is time dependent, changes in the shape of the geometries can be prescribed. Validation tests can be found in [2].

III. Deformability of the Geometry

To analyze the effects due to the bending and torsion motions acting on the blade, a simplified model is used. 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 and out of plane bending and torsion are uncoupled from each other.

The fourth-order Runge-Kutta method was used to solve both the equations.

A. 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.7)

$$I_\beta \ddot{\beta} + \beta[\Omega^2 (I_\beta + eRS_\beta) + K_\beta] = M_\beta \qquad (7)$$

Where

$$I_\beta = \int_{eR}^{R} m(r)(r - eR) \qquad (8)$$

$$K_\beta = (2\pi\omega_{NR})^2 I_\beta \qquad (9)$$

The “e” parameter is defining the location of the hinge along the blade [3]. 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.

B. 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.10).

$$I_\theta \ddot{\theta} + b\dot{\theta} + K_\theta \theta = M_\theta \qquad (10)$$

Where

$$I_\theta = I_G + Md^2 \qquad (11)$$

$$b = \varsigma(2\sqrt{K_\theta I_\theta}) \qquad (12)$$

$$K_\theta = (2\pi\Omega)^2 I_\theta \qquad (13)$$

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.

IV. Parametric Investigation

In order to perform the parametric analysis, several geometries have been generated (Fig. 1) by starting from a common baseline and changing the amount of sweep. The reference geometry is the Reference Wind Turbine (RWT) of the European project Upwind [4].

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

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

In order to consider the effects, due to the use of a swept blade on wind turbine performance, the lift distribution along the different blades, 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 Fig. 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. In accordance with the physics, 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.

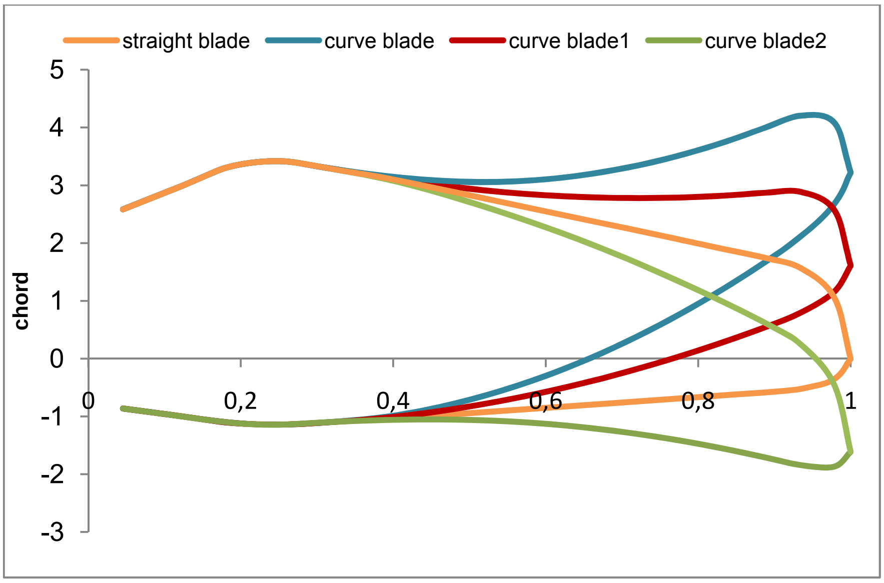

Fig. 1 Blade geometries used for the parametric analysis.

Table 2 Wind turbine performances referred to the reference geometry.

Blade ID	Power [W]	ΔPower (%)	Thrust [kN]	ΔThrust (%)
Straight blade	1891	/	367.94	/
Curve blade	1701	-10.1	292.29	-20.6
Curve blade 1	1830	-3.2	324.56	-11.8
Curve blade 2	1936	2.4	421.61	14.6

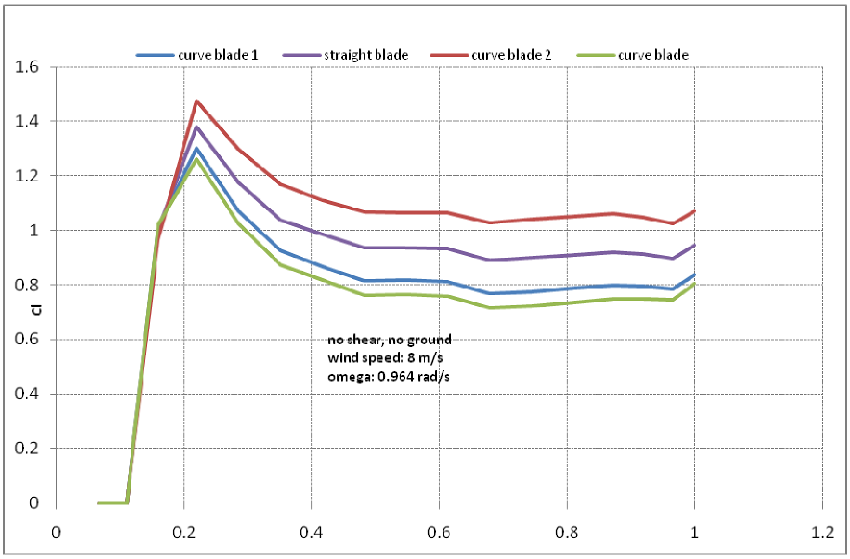

Fig. 2 Lift coefficient along the blade. Comparison between the geometries.

The same tests were carried out in presence of a gust, modeled according to the international standard IEC 61400-1[5]. A wind speed of 11 m/s and a rotational speed of 1.246 rad/s have been used for this simulation. Fig. 3 and Fig. 4 show the comparison in terms of time evolution of loads and of local angle of attack ,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.

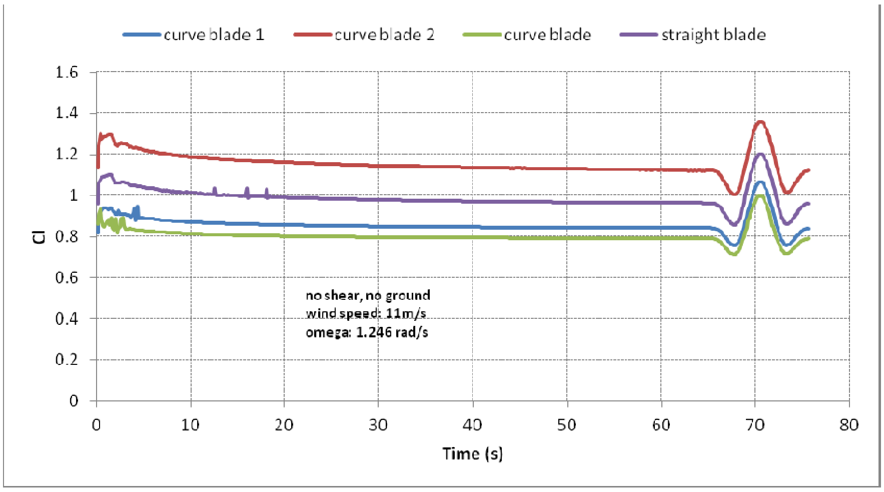

Fig. 3 Time evolution of local lift coefficient at 92% along the blade.

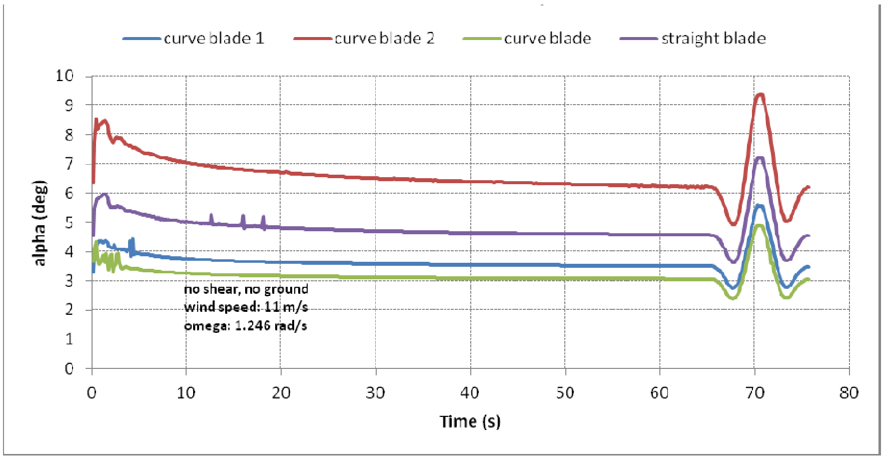

Fig. 4 Time evolution of local angle of attack at 92% along the blade.

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

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

V. 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 and costs related to the tower. Due to the reduction in local angle of attack along the blades, also the noise generated by the blade can be reduced by adopting these innovative geometries. Further studies focused on noise reductions are in development.

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