OPTIMUM BLADE DESIGN OF A 2 MW HORIZONTAL AXIS WIND TURBINE

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Abstract. *The present paper focuses on the development of a blade design tool for horizontal axis wind turbines with variable geometry. The design tool consists of an in-house MatLab program based on the Glauert Blade Element Theory, including tip and rotational wake losses as well as blade pitching and blade twisting effects. The program enables predictions of aerodynamic power, efficiency and forces acting on the wind turbine blades for a given operating condition. Numerical results in terms of aerodynamic performance are presented for a 2 MW wind turbine for a optimum blade shape.*

Keywords*: Wind Energy , Wind Turbine Blade Design*

1. INTRODUCTION

Since the demand for energy, more specifically electricity, has increased dramatically over the last 100 years, it has now become important to consider the environmental impacts of energy production. Therefore, there is general agreement that to avoid energy crisis, the amount of energy needed to sustain society will have to be contained and, to the extent possible, renewable sources will have to be used. As a consequence, conservation and renewable energy technologies are going to increase in importance and reliable, up-to-date information about their availability, efficiency, and cost is necessary for planning a secure energy future. Within this context, this paper focuses on the development of a blade design tool for horizontal axis wind turbines with variable geometry. The design tool consists of an in-house MatLab program based on the Glauert Blade Element Theory, including tip and rotational wake losses as well as blade pitching and blade twisting effects. The program enables predictions of aerodynamic power, efficiency and forces acting on the wind turbine blades for a given operating condition.

2. AERODYNAMICS OF WIND TURBINES AND OPTIMIZATION

A model attributed to Betz, can be used to determine the power from an ideal turbine rotor. This model is based on a linear momentum theory. Assuming a decrease in wind velocity between the free stream and the rotor plane, an axial induction factor, a, can be defined.

$$a = \frac{U - U_d}{U} \quad (1)$$

where, U is the free stream wind velocity and U_d is the wind velocity at the rotor plane disk.

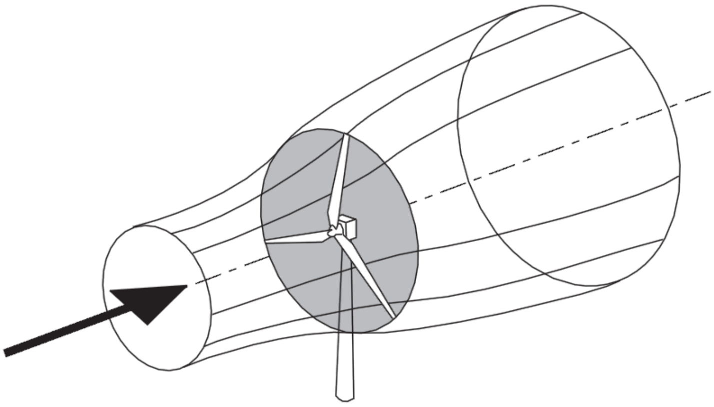

Figure 1. The Energy Extracting Stream-tube of a Wind Turbine.

The governing principle of conservation of flow momentum can be applied for both axial and circumferential directions. For the axial direction, the change in flow momentum along a stream-tube starting upstream, passing through the propeller disk area and then moving off into the slipstream, must equal the thrust produced by this element of the blade. To remove the unsteady effects due to the propeller's rotation, the stream-tube, according to Fig. 1 used is one covering the complete area, A, of the propeller disk swept out by the blade element and all variables are assumed to be time averaged values. The axial thrust on the rotor plane disk is given by:

$$T = \frac{1}{2}\rho A U^2 \left[4a(1-a)\right] \tag{2}$$

where ρ is the air density.

The power out, P, is equal to the thrust times the velocity at the disk:

$$P = \frac{1}{2}\rho A U^3 4a(1-a)^2 \tag{3}$$

Wind turbine rotor performance is usually characterized by its power coefficient, C_p, which represents the fraction of the power in the wind that is extracted by the rotor:

$$C_p = \frac{P}{\frac{1}{2}\rho U^3 A} = \frac{\text{Rotor power}}{\text{Power in the wind}} \tag{4}$$

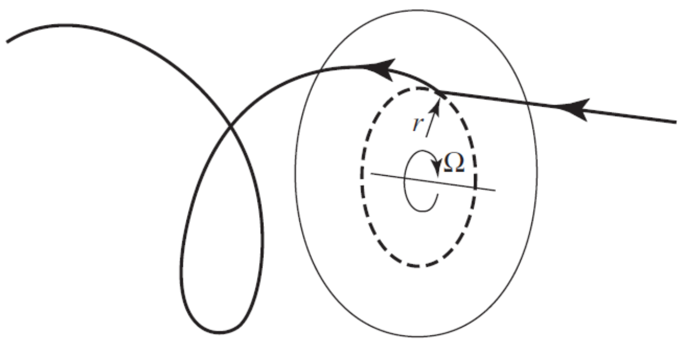

Figure 2. The Trajectory of an Air Particle Passing Through the Rotor Disc.

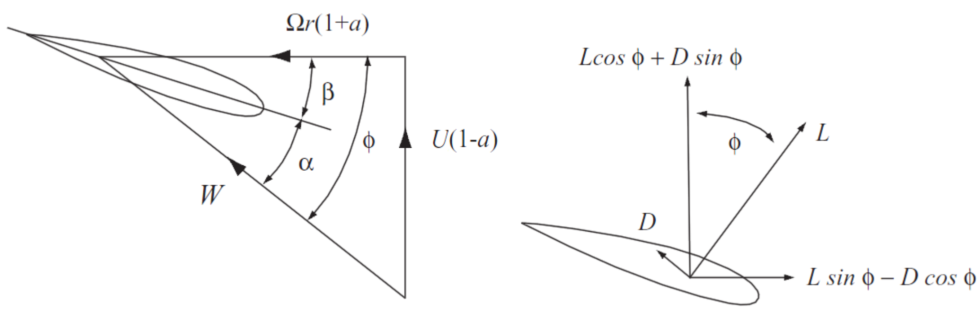

Figure 3. Blade Element Velocities and Forces.

If one considers the wake rotation, according to Fig. 2, where the angular velocity imparted to the flow stream is ω, while the angular velocity of the wind turbine rotor is Ω, then, across the flow disk, the angular velocity of the air relative to the blade increases from Ω to $\Omega + \omega$. One can prove that the tangential component of velocity is

$\Omega r(1+a)$, according to Fig. 3. In Fig. 3 α is the angle of attack, ϕ is the angle of relative wind and β is section pitch angle. Note that the angle of the relative wind is the sum of the section pitch angle and the angle of attack:

$$\phi = \beta + \alpha \tag{5}$$

Taking into account the lift force L and the drag force D, one can define the lift and the drag coefficients as:

$$C_l = \frac{L/l}{\frac{1}{2}\rho U^2 c} = \frac{\text{Lift force}/\text{unit lenght}}{\text{Dynamic force}/\text{unit lenght}} \tag{6}$$

$$C_d = \frac{D/l}{\frac{1}{2}\rho U^2 c} = \frac{\text{Drag force}/\text{unit lenght}}{\text{Dynamic force}/\text{unit lenght}} \tag{7}$$

From Fig. 3, one can determine the following relationships:

$$W = U(1-a)/\sin\phi \tag{8}$$

$$F_N = L\cos\phi + D\sin\phi \tag{9}$$

$$F_T = L\sin\phi - D\cos\phi \tag{10}$$

where W is the relative wind velocity, F_N is the normal force, and F_T is the tangential force to the disk.

If the rotor has B blades, the differential normal force on the section at the distance, r, from the centre is;

$$dF_N = B\frac{1}{2}\rho W^2 (C_l\cos\phi + C_d\sin\phi)cdr \tag{11}$$

The differential torque due to the tangential force operating at a distance, r, from the center is given by:

$$dQ = B\frac{1}{2}\rho W^2 (C_l\sin\phi - C_d\cos\phi)crdr \tag{12}$$

The power coefficient can be calculated as a function of the tip speed ratio λ and the local speed ratio λ_r (Gash and Twele, 2002),:

$$C_p = \left(8/\lambda^2\right)\int_{\lambda_h}^{\lambda} \sin^2\phi(\cos\phi - \lambda_r\sin\phi)(\sin\phi + \lambda_r\cos\phi)\left[1-\left(C_d/C_l\right)\cot\phi\right]\lambda_r^2 d\lambda_r \tag{13}$$

where

$$\lambda = \frac{\Omega R}{U} \tag{14}$$

and

$$\lambda_r = \lambda\, r/R \tag{15}$$

One can perform the optimization of the blade shape for an ideal rotor by taking the partial derivative of C_p which is a function of ϕ, and setting it equal to zero, to reveal that:

$$\phi = (2/3)\tan^{-1}(1/\lambda_r) \tag{16}$$

$$c = \frac{8\pi r}{BC_l}(1-\cos\phi) \tag{17}$$

Applying the Blade Element Theory (Donadon, 2008), the total wind turbine thrust and torque is obtained by summing the results of all the radial blade elements along the radial direction, that is:

$$\begin{aligned} T &= \sum_{i=1}^{N} \Delta T \\ Q &= \sum_{i=1}^{N} \Delta Q \end{aligned} \tag{18}$$

where N is the number of blade elements along the radial direction.

3. ITERATIVE SOLUTION PROCEDURE FOR BLADE ELEMENT THEORY

The iterative solution procedure for the Blade Element Theory is described below:

1) The method of solution for the blade element flow must start with some initial guess of R and λ.

2) Use these to find the flow angle on the blade according to Eq. (16), and then, use Eq. (17) to estimate the chord. Element thrust and torque are obtained from Eqs. (11) and (12) adapted to a finite radial length according to Eq. (18). Accordingly, the power coefficient can be estimated from Eq. (13).

3) With these approximate values of thrust and torque, Eqs. (16) and (17) can be used to give improved estimates of the flow angle and chord. This process can be repeated until values for ϕ and c have converged to within a specified tolerance. It should be noted that convergence for this nonlinear system of equations is not guaranteed. It is usually a simple matter of applying some convergence enhancing techniques (ie Crank-Nicholson under-relaxation) to get a result when linear aerofoil section properties are used. When non-linear properties are used, including stall effects, then obtaining convergence will be significantly more difficult.

4) For the final values of ϕ and c, an accurate prediction of element thrust and torque will be obtained from equations (18).

4. NUMERICAL SIMULATIONS

The theory presented in the previous section was used to predict the aerodynamic performance of a 2 MW wind turbine. The wind turbine has three blades equally spaced along the circumferential direction. For the present work, the aerodynamic characteristic curves in terms of lift coefficient versus angle of attack and drag coefficient versus angle of attack of a NACA 4412 airfoil was taken into account. The adopted criterion for choosing the best airfoil for the wind turbine blade is based on how much aerodynamic power the airfoil can effectively generate and transfer to the wind turbine shaft for a given operating condition. This quantity is measured by the power coefficient C_p which is defined by the ratio between aerodynamic power and wind power, (Gash and Twele, 2002). The turbine's aerodynamic performance was evaluated for each one of the three airfoils described previously using an in-house MatLab program based on the *Glauert Blade Element Theory* cited in section 2. For the studied case the same airfoil was used in all sections of the blade along the radius direction.

Table 1 presents values of the input data U and N, adopted for the numerical simulation. The same table also presents final values for C_p , R, T and Q. For the simulated case, the air properties were considered for sea level at 20^o C.

Figure 4 shows the behavior of the blade chord along the blade radius direction. Figure 5 presents the variation of ϕ along the radius direction. In both figures, the chord c and the angle ϕ were normalized according to the maximum values. The present code also allows one to obtain the x and y coordinates of the blade sections after rotation. For example, the profiles of sections 1,6,24,48,72 and 96 are illustrated in Fig. 6. An illustrative picture of the blade appearance is presented in Fig. 7.

Table 1. Initial data and final results for a 2 Mw wind turbine blade.

U	12.5 m/s
N	96
C_p	0.4956
R	34.8253 m
T	1.8286×10^4 N
Q	4.9485×10^4 N.m

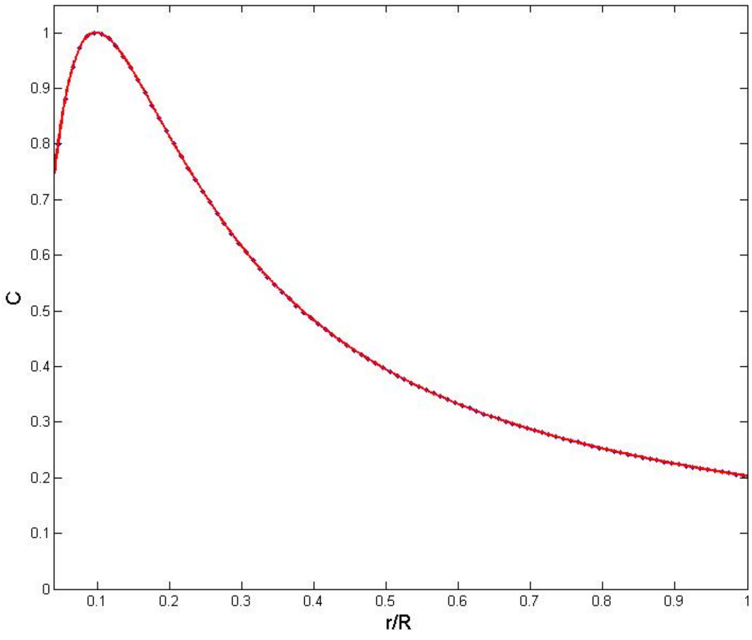

Figure 4. Blade chord along radius direction.

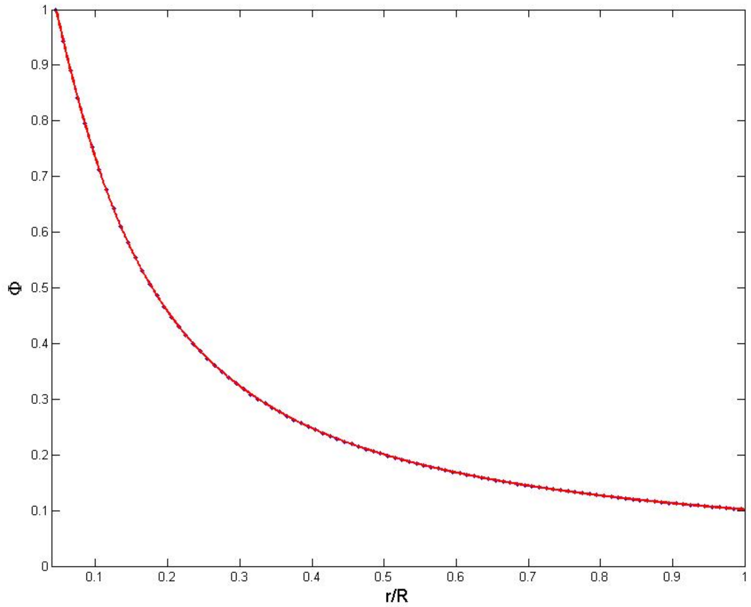

Figure 5. Blade angle ϕ along radius direction.

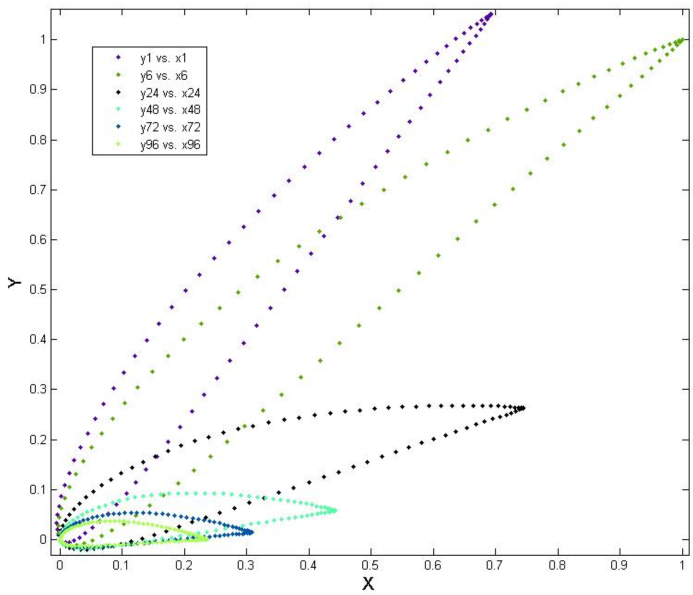

Fig. 6. Illustration of the blade profiles for sections 1,6,24,48,72 and 96.

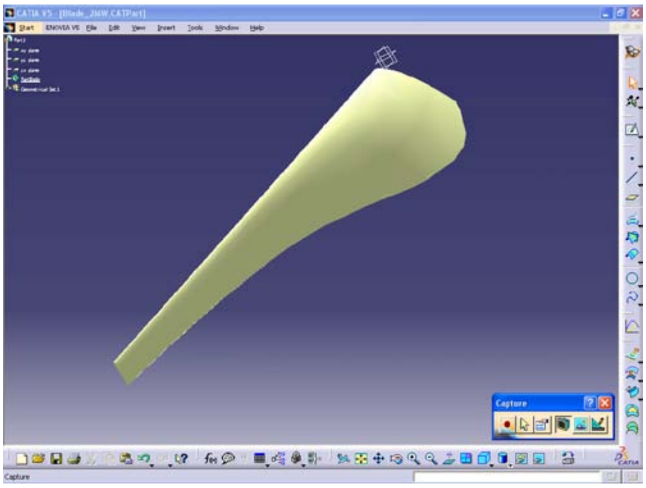

Figure 7. An illustrative picture of the blade appearance.

4. CONCLUSIONS

An aerodynamic model for wind turbines with variable geometry was presented and discussed in this work. Details about the numerical implementation were also presented and discussed. The proposed formulation is based on the Glauert Blade Element Theory which accounts for tip and rotational wake losses, which enables the prediction of torque, thrust and power coefficient for wind turbines with different airfoils geometries and subjected to a wide range of operating conditions. A study case in terms of aerodynamic performance was presented for a 2 MW wind turbine, in which a nominal velocity of 12.5 m/s was considered. The numerical predictions indicated a final radius R and a C_p value coherent with expected values for a 2 MW wind turbine blade. The same results may be compared with wind turbine blades commercially adopted.

5. ACKNOWLEDGEMENTS

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