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OPTIMUM BLADE DESIGN FOR A 1,5 MW WIND TURBINE

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Abstract: *This paper shows a numerical procedure for the optimal aerodynamic design of a wind turbine blade. The particular case for a 1.5MW wind turbine is evaluated. In this procedure an in-house MatLab program based in the Glauert´s Blade Element Theory is used. Tip and rotational wake losses effects are included, as well as blade pitching and twisting ones. The optimal design is obtained in order to determinate the higher power coefficient Cp possible for a monolithic blade.*

Keywords: *wind turbine; blade design; blade element theory*

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 reliability. 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 (Burton, 2001), 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.

Blade element theory (BET) is a mathematical process originally designed by William Froude (1878), David W. Taylor (1893) and Stefan Drzewiecki to determine the behavior of propellers. Glauert adapted the theory to wind turbines. Blade element theory attempts to address information on rotor performance or blade design by considering the effects of blade design i.e. shape, section, twist, etc. Blade element theory models the rotor as a set of isolated two-dimensional blade elements to which we can then apply 2-dimensional aerodynamic theory individually and then perform an integration to find thrust and torque.

2. AERODYNAMICS OF WIND TURBINES AND OPTIMIZATION

A model attributed to Betz (Burton, 2001), 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 as

$$a = \frac{U - U_d}{U}, \tag{1}$$

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

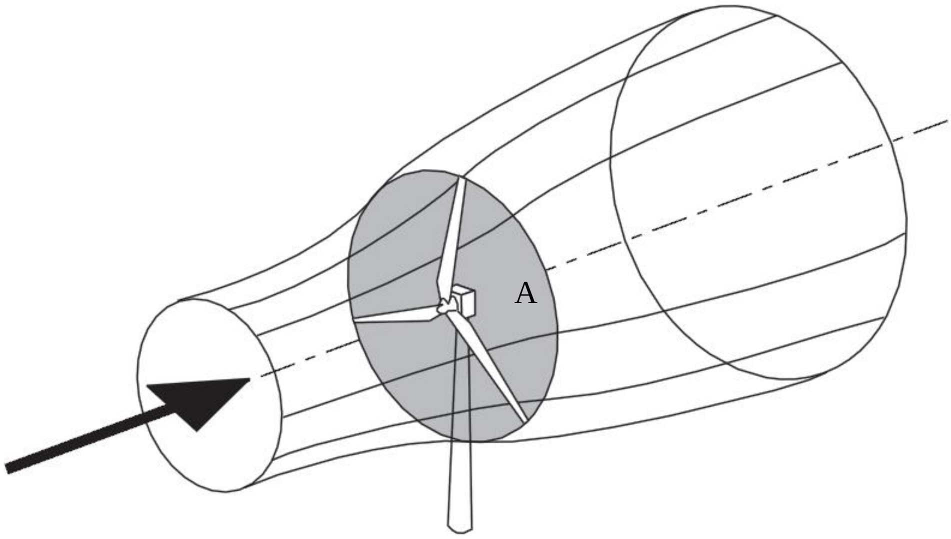

Figure 1. The Energy Extracting Stream-tube of a Wind Turbine.

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.

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

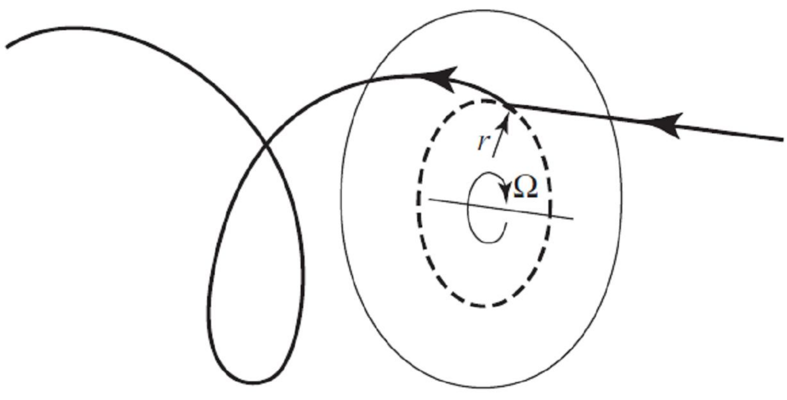

Figure 2. The Trajectory of an Air Particle Passing Through the Rotor Disc.

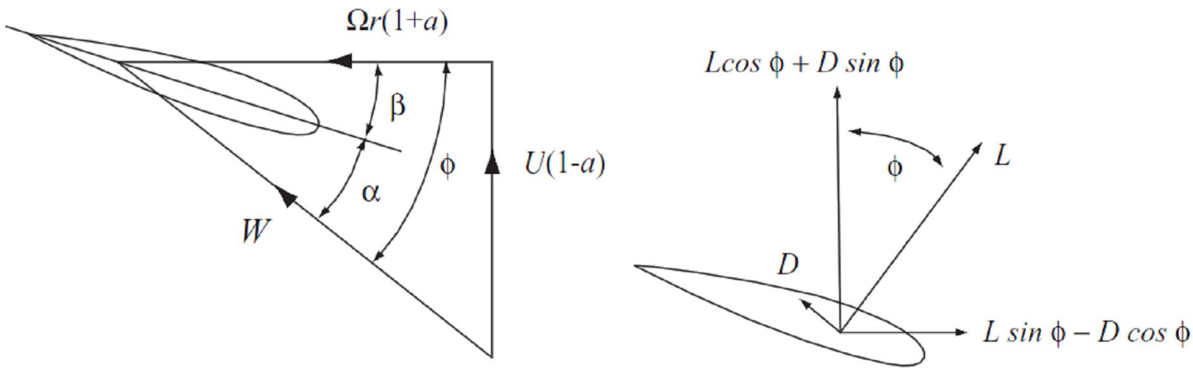

Figure 3. Blade Element Velocities and Forces.

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 ω + **Ω**. One can prove that the tangential component of velocity is **Ω** 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.

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

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

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

and

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

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

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

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

and

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

where W is the relative wind velocity, N_F 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

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

and

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

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) by

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

where

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

and

$$\lambda_r = \lambda\frac{r}{R}. \tag{15}$$

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

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

and

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

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

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

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

3. SOLUTION PROCEDURE FOR BLADE ELEMENT THEORY

The analysis described assumes that all fluid particles undergo the same loss of momentum, i.e., there are a sufficient number of blades on the rotor for every fluid particle passing through the rotor disc to interact with a blade. With a small number of blades some fluid particles will interact with them but most will pass between the blades and, clearly, the loss of momentum by a particle will depend on its proximity to a blade as the particle passes through the rotor disc.

If the axial flow induction factor a is large at the blade position then the inflow angle will be small and the lift force will be almost normal to the rotor plane. The component of the lift force in the tangential direction will be small and so will be its contribution to the torque. A reduced torque means reduced power and this reduction is known as tip loss because the effect occurs only at the outermost parts of the blades.

In agreement with Burton (2001) this tip loss can be described with Prandtl's approximation.

$$f_T(\mu) = \frac{2}{\pi}\cos^{-1} e^{\left(-\frac{\frac{B}{2}(1-\mu)}{\mu}\right)\sqrt{1+\frac{(\lambda\mu)^2}{(1-a)^2}}}, \tag{19}$$

where $\mu = \frac{r}{R}$.

At the root of a blade the circulation must fall to zero as it does at the blade tip and so it can be presumed that a similar process occurs. The blade root will be at some distance from the rotor axis and the airflow through the disc inside the blade root radius will be at the free-stream velocity. It is usual, therefore, to apply the Prandtl tip-loss function at the blade root as well as at the tip.

$$f_R(\mu) = \frac{2}{\pi}\cos^{-1} e^{\left(-\frac{B}{2}\left(1-\frac{\mu_R}{\mu}\right)\right)\sqrt{1+\frac{(\lambda\mu)^2}{(1-a)^2}}}, \tag{20}$$

where μ_R refers the position of the hub.

So, the tip/root loss factor is written as

$$f(\mu) = f_T(\mu) f_R(\mu). \tag{21}$$

The tip/root loss factor leads to the new value of the induction factor.

$$a = \frac{1}{3} + \frac{1}{3}f - \frac{1}{3}\sqrt{1-f+f^2}. \tag{22}$$

Once this induction factor is know, its derivative also is obtained.

$$a' = \frac{1}{(\lambda\mu)^2} a\left(1-\frac{a}{f}\right). \tag{23}$$

Now, with the derivative of Eq. (13) with respect to μ can be written. It represents the span-wise variation of power extraction in the presence of losses.

$$R\frac{dC_p}{dr} = 8(1-a)a'\lambda^2\mu^3. \tag{24}$$

The new inflow angle can be determined by

$$\phi = \tan^{-1}\frac{1-\frac{a}{f}}{\lambda\mu\left(1+a\frac{1-\frac{a}{f}}{f(\lambda\mu)^2}\right)}. \tag{25}$$

The power coefficient can be found now. Considering the Blade Element Theory already nominated and using equation 24, the C_p is obtained by a summation of all blade elements. Once C_p is already estimated the diameter of the rotor can be found.

4. NUMERICAL SIMULATIONS

The theory presented in the previous section was used to predict the aerodynamic performance of a 1,5 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 sections 2 and 3. For the studied case the same airfoil was used in all sections of the blade along the radius direction.

It is considered

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°C.

Table 1. Inicial data and final results for a 1,5 MW wind turbine

U	12.5 m/s
N	90
C_p	0.549
R	32.51 m
T	2.56×10^3 N
Q	1.84×10^3 N.m

Figure 4 shows the behavior of the blade chord along the blade radius direction. Figure 5 presents the variation of β along the radius direction. In both figures, the chord c and the angle β were normalized according to the maximum values.

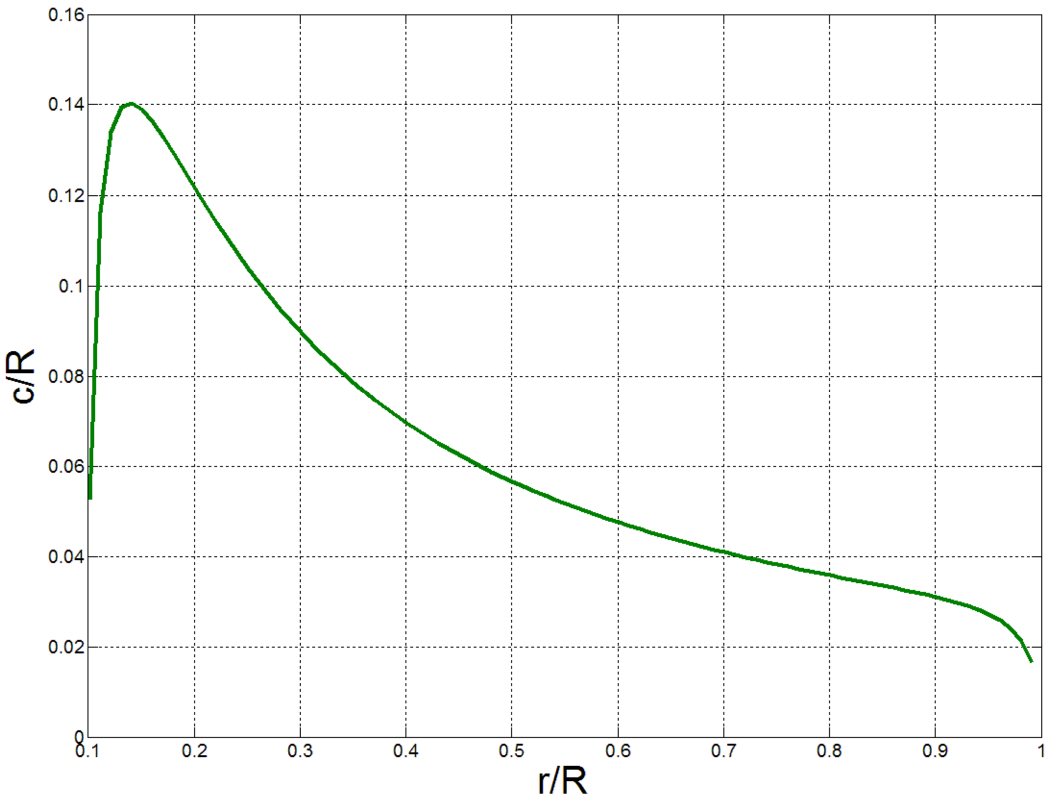

Figure 4. Blade chord along radius direction.

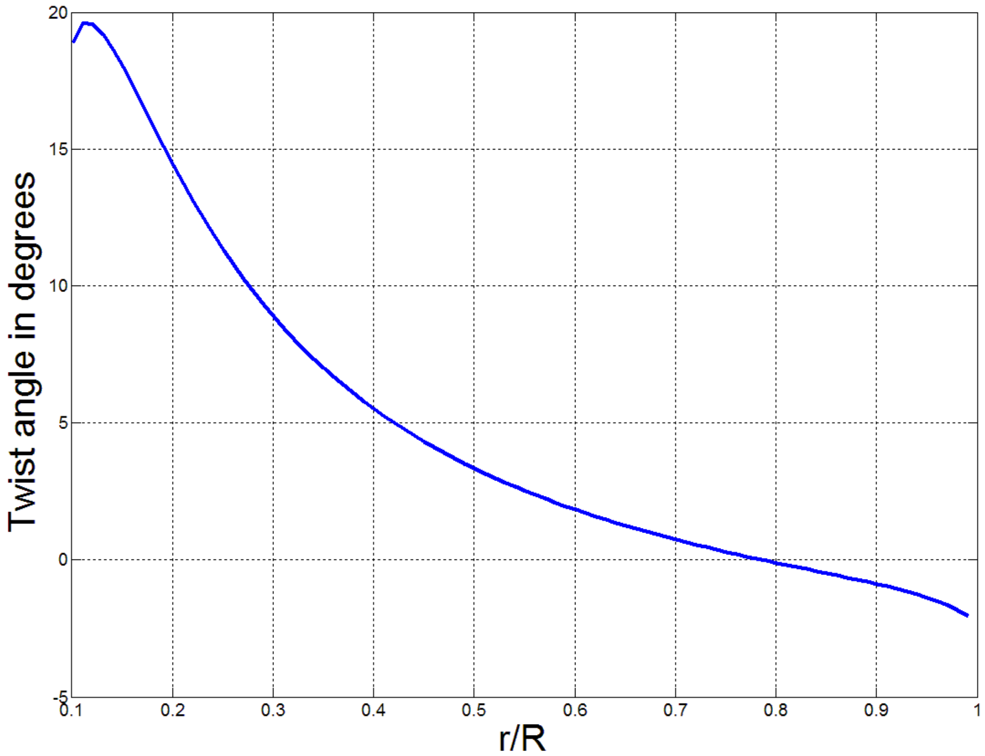

Figure 5. Blade twist angle along radius direction.

Figure 6 shows the tip/root loss factor based on de Prandtl´s approximation. Figure 7 presents the power extraction along the blade span. It can be notice that the major amount of energy is extracted at a region near the tip of the blade. The contribution of region near de hub is minimal.

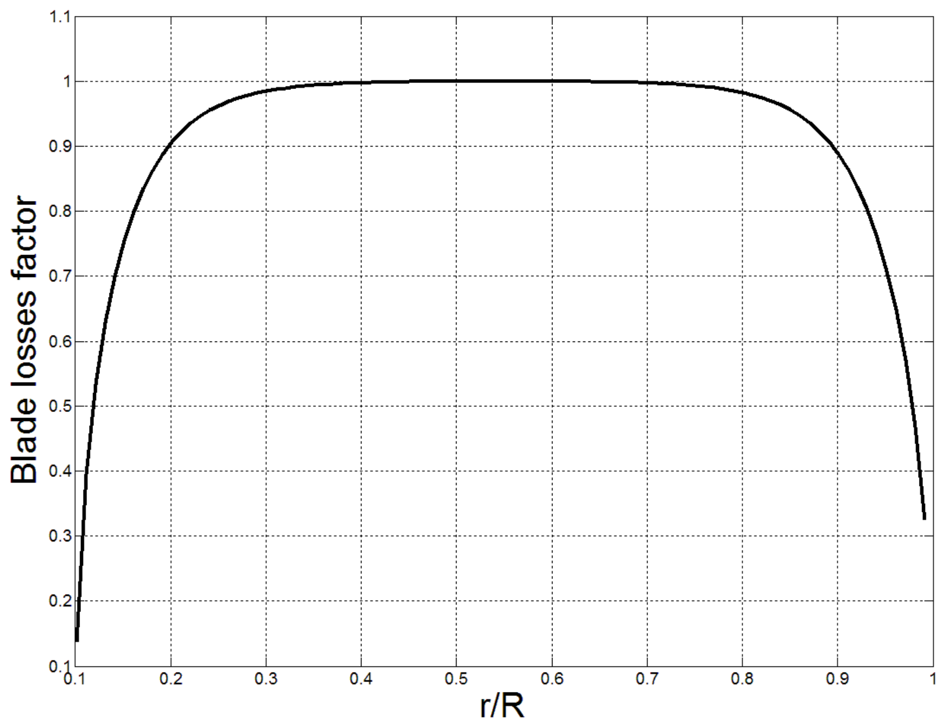

Figure 6. Tip/root loss factor.

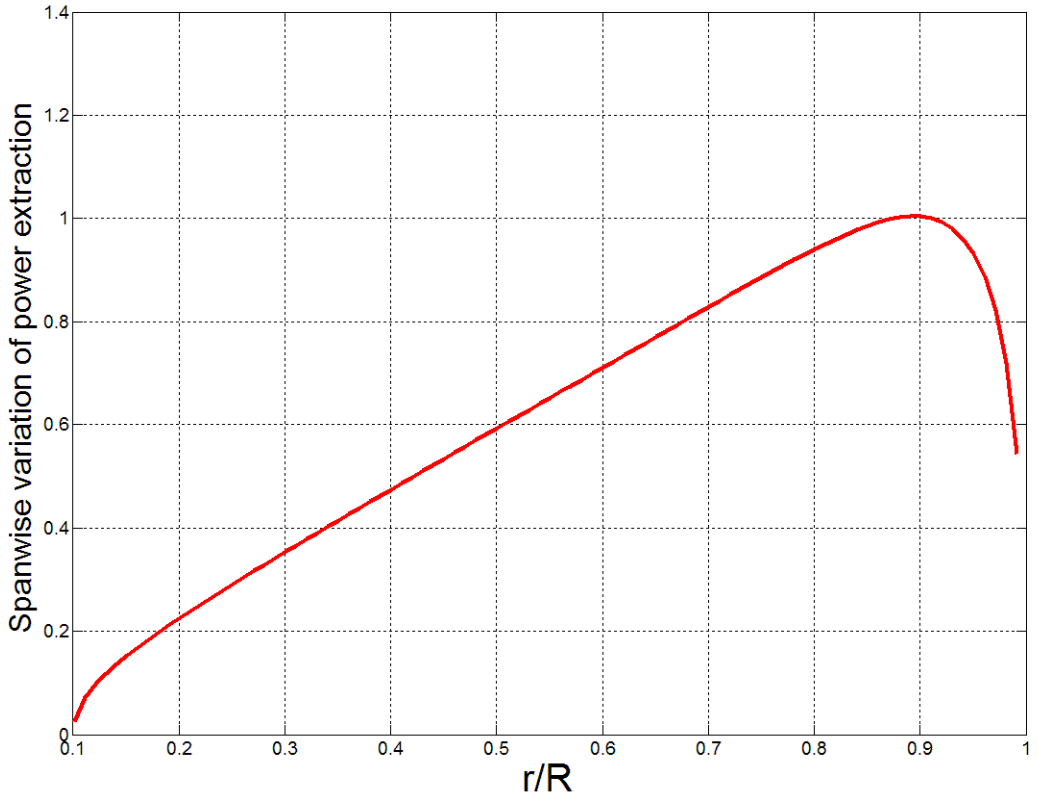

Figure 7. Power extraction along radius direction.

5. 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 described with Prandtl's approximation, 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 1.5 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 1.5 MW wind turbine blade. The same results may be compared with wind turbine blades commercially adopted.

6. ACKNOWLEDGEMENTS

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