COMPUTATIONAL PREDICTION OF POWER LOSSES IN SMALL SCALE WIND TURBINES DUE TO DIFFERENCES IN TAPER DESIGN CRITERIA

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Abstract. *The most important feature of a wind turbine blade is the ability to extract as maximum energy as possible of the wind to generate high torque on the axis. To achieve this propose the design of the blade have certain criteria to keep each section along the radius direction in best aerodynamic configuration, whereas the resultant velocity in this direction change from the root to the tip. The design criteria used by the Blade Element Momentum – BEM to develop the curves of twist angle and chord span-wise variation have two approaches. The first one provides the best results of efficiency but the construction of the blade is difficult, because the curves of twist angle and chord span-wise variation are non-linear. The second one proposes the correction of the chord span-wise variation curve to make it linear, however this modification decreases the efficiency, whereas modify all the other parameters. This approach of the chord span-wise variation curve correction makes the construction of the blade simpler. This work used a Computational Fluid Dynamics – CFD package to compare the percentage reduction of the efficiency between the both approaches. The number of blades per rotor was three and the profile applied to design the blades was the NACA6412. The software used to perform the simulation was OpenFOAM, which is an open source package for CFD solutions. The present work is supported by the FUNCAP/CNPq/Modernização de Laboratórios.*

Keywords*: wind turbine; chord span-wise variation method of project; OpenFOAM; RANS turbulence models.*

1. INTRODUCTION

In a wind turbine the ability of the blades to extract energy of the wind flux determines the energy available for the rest of the system. With this in mind, the aerodynamic efficiency of the blades is the first problem to be solved to obtain an efficient apparatus. Nowadays the design of the blades still represent a challenge, since the problems that involve three-dimensional flows are very difficult even with the evolution of the computer resources and the CFD (Computational Fluid Dynamics) applications. Not only the design represents a big effort, since the preparing of the structure and construction become a more difficult task.

The design of the blade can be done by two ways using the BEM (Blade Element Momentum) theory. The first one searches for the best configuration to get the highest values of efficiency, but this approach makes the blade construction very difficult, because it is necessary to associate the twist angle with a non linear chord span-wise variation in the same fabrication process. The second way corrects the curve of chord span-wise by taking a tangent line of it to make its variation linear (BURTON *et al*, 2001).

The BEM theory considers that the flow over the blade is two-dimensional in each section. All the three-dimensional effects are neglected and the correction for the curve’s linearization chord span-wise results in modifications of the twist angle too. By this approach the efficiency of the blade is known to be worse than the non linear chord span-wise variation project, but the impact of this correction isn’t quantified by the method. There is also a lack of information in the literature about this quantity.

The main goal of this work is the preview of the efficiency loss between the two design criteria, through the evaluation of the percentage differences in the efficiency curves. The simulations used a RANS (Reynolds Averaged Navier-Stokes) turbulence model. The flow was calculated by a steady, incompressible, turbulent solver, provided by the OpenFOAM (TABOR *et al*, 1998) CFD package.

2. METHODOLOGY

This work used the NACA 6412 airfoil to design two set of blades, both to operate under TSR=5 (Tip Speed Ratio). One of them was designed with the non linear chord span-wise variation, and the other was corrected to make de chord span-wise linear.

Both projects were simulated applying RANS models, namely the k-ε and the k-ω SST, and also a laminar model to evaluate the percentage differences.

2.1 Blade design

The blade design by the BEM theory considers the two-dimensional flow in each section and the integration doesn't consider the drag effect (BURTON *et al.*, 2001).

2.1.1 Design with a non linear chord span-wise variation

The Equations 1 and 2 were respectively used to set up the curves of the chord span-wise variation and the twist angle variation. The value of C_l was a parameter of the blade and was get by the higher relation of C_l/C_d of the chosen airfoil.

$$\frac{Nc}{2\pi R}\lambda C_l = \frac{\frac{8}{9}}{\sqrt{\left(1-\frac{1}{3}\right)^2 + \lambda^2\mu^2\left[1+\left(\frac{2}{9(\lambda^2\mu^2)}\right)\right]^2}} \tag{1}$$

In this equation, N is the number of blades, c is the chord, R is the radius of the rotor, λ is the design TSR, C_l is the lift coefficient of the airfoil that gives the higher C_l/C_d relation and μ is the dimensionless radius position.

In this work the angle of attack value, α, was fixed in the condition of the higher C_l/C_d relation for the airfoil, so the twist angle variation, β, was only dependent of the resultant velocity condition in each radius location, φ. So the twist angle was calculated by the Equation 3.

$$\tan\emptyset = \frac{1-\frac{1}{3}}{\lambda\mu\left(1+\frac{2}{3\lambda^2\mu^2}\right)} \tag{2}$$

$$\beta = \emptyset - \alpha \tag{3}$$

2.1.2 Design with a linear chord span-wise variation

The corrected chord c_u is described by the tangent line of the curve represented by the Equation 1 and is presented in Equation 4. The same consideration made for the C_l value in the Equation 1 is valid for Equation 4.

$$\frac{c_u}{R} = \frac{8}{9\lambda 0,8}\left(2-\frac{\lambda\mu}{\lambda 0,8}\right)\frac{2\pi}{C_l\lambda N} \tag{4}$$

In this case the value of C_l is not a parameter and has to be corrected by Equation 5, and the angle of attack are not fixed. So the correction of the chord span-wise was made, the profile of the twist angle is described by Equation 2 and 6 and calculated by Equation 3.

$$C_l = \frac{\frac{8}{9}}{\frac{Nc_u\lambda}{2\pi}\sqrt{\left(1-\frac{1}{3}\right)^2 + \lambda^2\mu^2\left[1+\left(\frac{2}{9(\lambda^2\mu^2)}\right)\right]^2}} \tag{5}$$

$$\alpha = \frac{C_l}{m} + \delta \tag{6}$$

Where δ is the zero lift angle of attack for the airfoil adopted in the blade design.

In both approaches it was necessary in the twist angle (β) deducing, the zero lift angle of attack for the airfoil, δ.

2.2 Mesh parameterization

The size and refinement parameterization of the mesh around the wind turbine was made to guarantee that the grid independence was achieved. The first step was to analyze the optimal lengths in the downstream and upstream directions. Then the second step analyzed the parameterization of the transversal section and the refinement region areas. This refinement area has to be large enough to ensure that the all aerodynamic effects (mainly tip losses) are inside the refined region. (Carneiro e*t al*, 2009)

2.3 Simulation parameters

Each point of the efficiency curve represents one simulation with a fixed TSR condition. Since the wind speed was defined as constant and equal to 6,5 m/s, the boundary condition of rotation started with the angular velocity corresponding to TSR=1 and finished with the value of TSR in which the blade did not give any torque in the same rotation direction. So in order to get the curve it was necessary to perform many simulations with different boundary conditions of the rotor's angular velocity. These conditions of rotation are showed in Table 1.

Table 1 – Boundary conditions of rotor's angular velocity

TSR	Angular velocity applied as boundary condition for the rotor
1	4,333rad/s
2	8,666rad/s
3	13,000rad/s
4	17,333rad/s
5	21,666rad/s
6	26,000rad/s
7	30,333rad/s
8	34,666rad/s

Besides the condition of movement other conditions were necessary to be set up. For the RANS models k-ε and k-ω SST it was calculated the initial value of the field for k, ε and ω, considering the turbulence intensity equal to 20% and the characteristic length equal to 6m. The last one was referred as the diameter of the circular transversal section of the control volume assumed by the parameterization results. For all of the simulations it was adopted the interpolation scheme GAMMA 1 (Jasak *el al*, 1999) for the velocity and the scheme UPWIND for the fields of p, k, ε and ω. The Table 2 shows the general boundary conditions applied.

Table 2 – General boundary conditions

Region of the mesh	**Boundary conditions**				
	Velocity	**Pressure**	**k**	**ε**	**ω**
Inlet	6,5 m/s	Zero Gradient	0,634 m^2/s^2	26,141m^2/s^3	41,248/s
Outlet	Zero Gradient	0 Pa	Zero Gradient	Zero Gradient	Zero Gradient
Contour	Slip	Slip	Slip	Slip	Slip
Rotor	*Table 3.1*	Zero Gradient	Zero Gradient	Zero Gradient	Zero Gradient

The numerical instability varies for each operational condition simulated, so the relaxation factors were adjusted considering the most instable one. The worst one converged after 1000 steps, and then all the simulations were set up to finish with this number of steps. This last consideration was necessary for the solution to reach the steady state condition.

3. RESULTS AND DISCUSSIONS

3.1 Blade design

The designed chord span-wise curve that was corrected to a linear fit has the chord length near the root smaller than the non linear project. This happens because the linearization correction considers that the linear curve is tangent of the non linear one at the point of 80%, as seen in the Figure 1. The same behavior was observed in the twist angle curves. The correction decreases the angles near the blade root.

The curves of chord span-wise and twist angle for both designs are demonstrated in Figures 1 and 2, respectively.

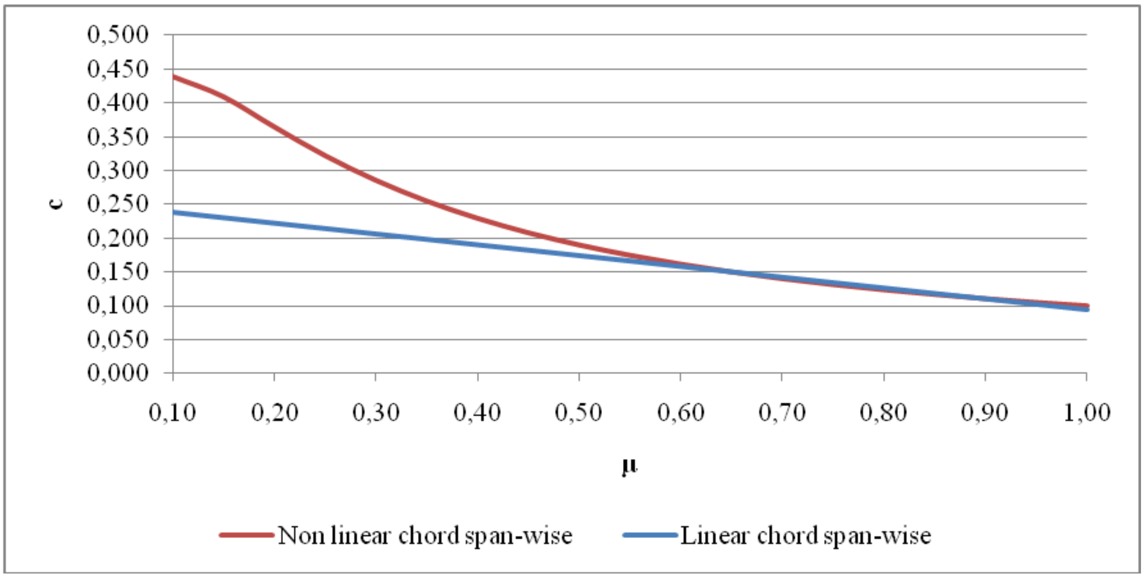

Figure 1 – Chord span-wise curves for the both approaches – Non linear and linear chord span-wise.

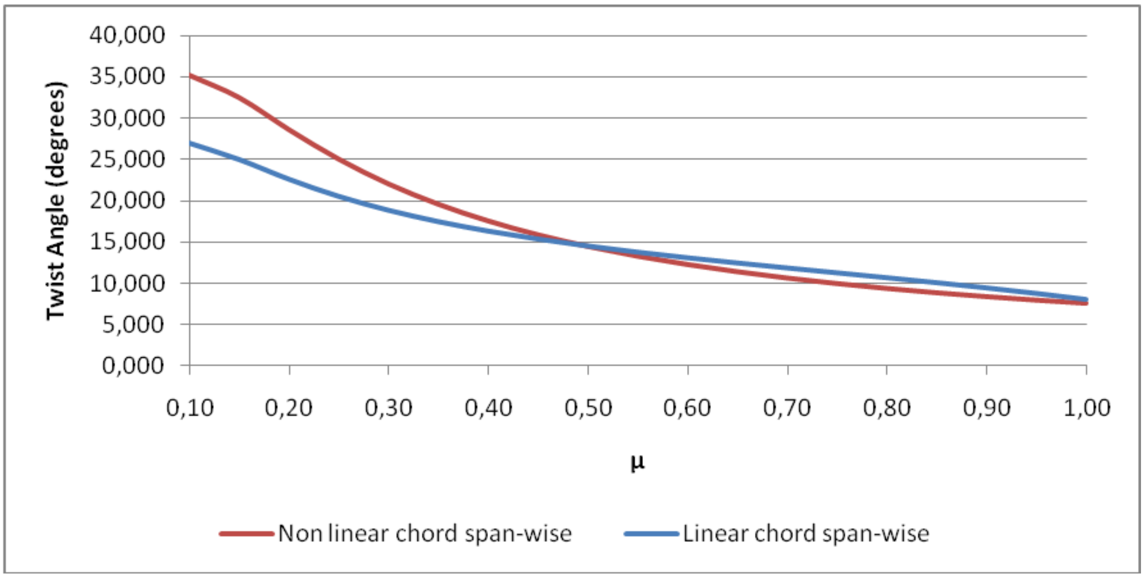

Figure 2 – Twist angle curves for the both approaches – Non linear and linear chord span-wise.

3.2 Numerical Results

The results demonstrated that the project with non linear chord span-wise variation gives the best values of C_p independently of the adopted numerical model. The RANS model k-ω SST gives the highest values of efficiency among the tested models.

Figures 3, 4 and 5 show the efficiency curves obtained, respectively, with the k-ε, k-ω SST and laminar models.

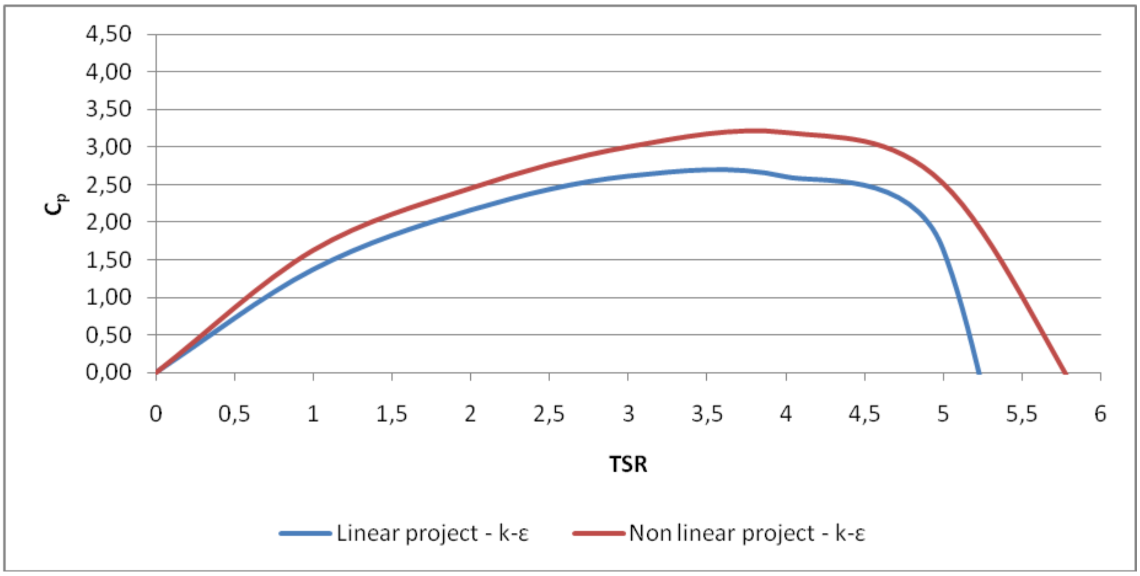

Figure 3 – Efficiency curve, C_p versus λ, acquired by simulations with the RANS model k-ε.

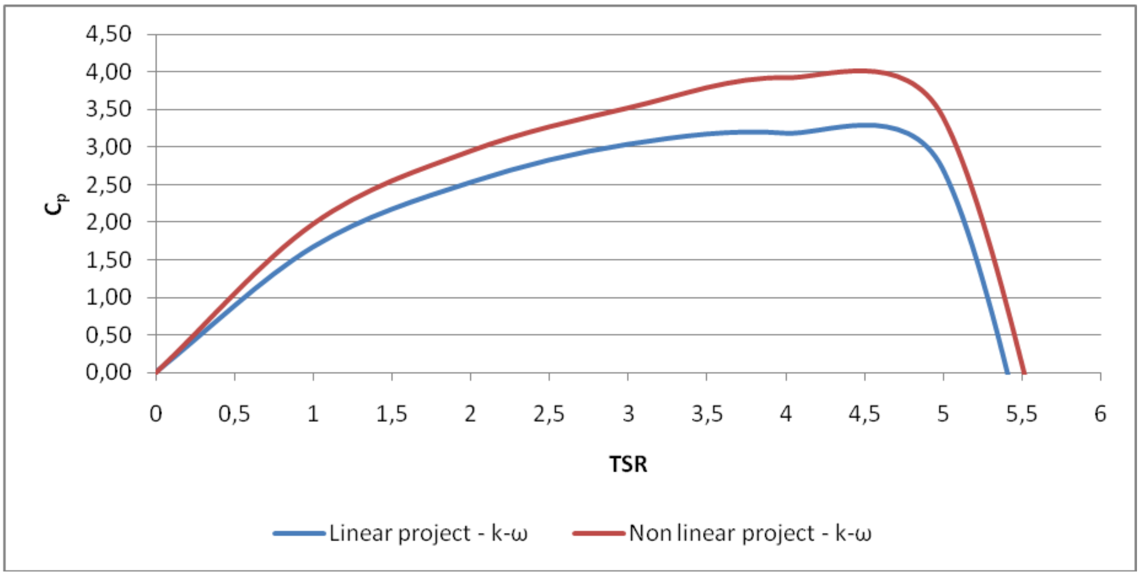

Figure 4 – Efficiency curve, C_p versus λ, acquired by simulations with the RANS model k-ω SST.

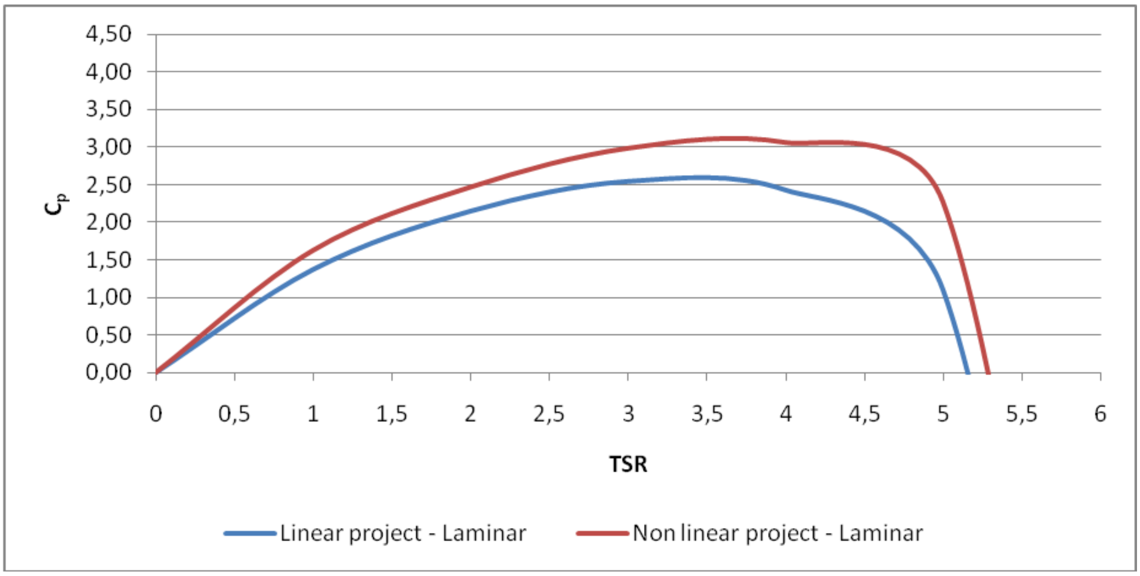

Figure 5 – Efficiency curve, C_p vesus λ, acquired by simulations with the Laminar model.

Figure 4 indicates that the best result was C_p = 4% when the rotor operated at TSR = 4,5, approximately. This value of tip speed ratio is very close of the value one of the project, TSR=5.

It is possible to see in Figure 5 that the percentage gain in the nonlinear approach has the same behavior for all models and was positive for any value of TSR. Nevertheless, close to the designed TSR (in this case 5), where the blade operates under the best conditions (extracting the highest values of energy), the percentage gain was higher, but quite different between the models. This can be explained because at this stage the blades start to stall, which is a phenomenon very difficult to model.

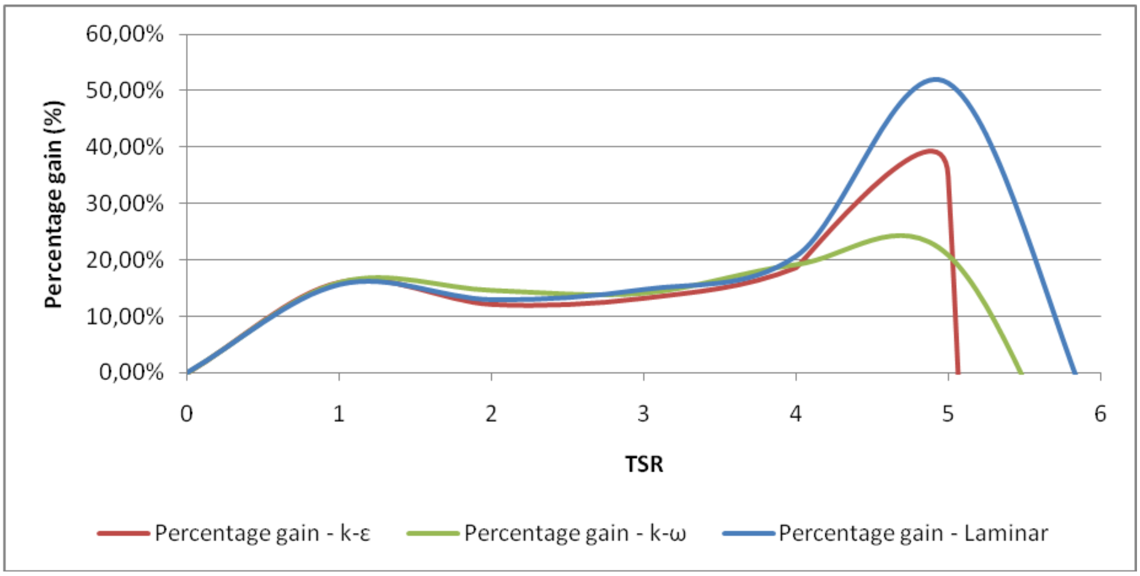

Figure 5 – Percentage gain varation by TSR for witch RANS model.

4. CONCLUSION

The design of the blade and numerical analysis in order to quantify the losses caused by the linearization of the chord span-wise variation was performed successfully.

The correction to make the chord span-wise linear facilitates the construction of the blade but reduces the efficiency of the rotor by two ways. The first one is a decrease in power extraction of the wind, which consequently diminishes the C_p value. The other one is a narrowing of the TSR operational range.

All the results show the same behavior of efficiency gain by the nonlinear chord span-wise variation design. The percentage gain was 15% in average, but when the blade operate at the designed TSR 5, it was possible to see that the gain was bigger than 35%.

The presented results show coherence with the physical problem, since the linear design makes the blades to operate in a non ideal condition for the airfoil characteristics. The angle of attack (α) is not fixed at the higher C_l/C_d relation for the airfoil in any radial condition.

After this numerical analysis, experimental tests are in progress in order to verify how big are the losses and which model gave the best results.

3. ACKNOWLEDGEMENTS

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