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WIND TURBINE BLADES DESIGNED TO THE WIND CONDITIONS OF AJURUTEUA BEACH

Erick Oliveira do Nascimento[1]
Ruan de Souza Ribeiro[2]
Davi Cavalcante de Oliveira[3]
Jerson Rogério Pinheiro Vaz[4]
Federal University of Pará, Graduate Program in Mechanical Engineering. Augusto Corrêa Avenue, 1, Guamá, 66075-110. Belém, PA, Brazil
[1]oliveira94n@gmail.com, [2]ruan.ribeiro@tucurui.ufpa.br, [3]daviufpappgem@gmail.com, [4]jerson@ufpa.br

Abstract. *Small wind turbine of horizontal axis in general are subjected to low wind speed, very common in remote areas as in the region of Ajuruteua, in the state of Pará. This paper concentrates on the use of blade element theory to design a small wind rotor adapted to Ajuruteua beach, whose average wind condition is about 8.84 m/s. The approach applies Prandt's and Glauert's formulations to optimize the aerodynamic blades of a small wind rotor. NACA 654-421 airfoil is employed, in order to design a more suitable turbine to the Ajuruteua's wind condition, a computational code was developed to optimize the airfoil. The results showed that the best power coefficient achieved is 39%, generating a power output of 1200 W for a wind speed of 10 m/s.*

Keywords: *blade element theory, optimize, airfoil, computational code*

1. INTRODUCTION

The study of aerodynamic design applied to wind turbine blades, has become significant due to the increasing use of renewable energy sources with low environmental impact. Even for moderate wind speeds, the small wind turbines are a very attractive way for generating electricity.

The International Electrotechnical Commission, through the standard IEC 61400-2, consider the small wind turbines as having a rotor swept area smaller than or equal to 200 m², generating electricity at a voltage below to 1000 V a.c. or 1500 V d.c. for both on-grid and off-grid applications. These turbines are used typically in remote area power systems, often in conjunction with a diesel/electric generators and a battery system to supply power to a single user or a small grid (Clausen and Wood, 1999).

The purpose of most wind turbines is to extract as much energy from the wind as possible and each component of the turbine has to be optimized for that goal (Burton et al., 2001). An important step from an essentially physical approach to technical rotor aerodynamics is taken by introducing rotor blade geometry. Hau (2013), states that the Blade Element Theory (BET) provides the distribution of aerodynamic forces over the length of the blade. This is usually divided into two components: one in the plane of rotation of the rotor, the tangential force distribution, and one at right angles to it, the thrust distribution. The blade element thus provides both the rotor power and the steady-state aerodynamic loading for a given blade geometry.

For estimating the wind power potential of a region requires systematic research on data collection and analysis of wind speed and its regime. In order to correctly evaluate the feasibility of the implantation of a wind farm, it is required that wind measurements (velocity and direction) be made at specified heights in locations chosen for their potentially strong winds. The same consideration of data integrity can be adopted in the analysis of wind direction, shape factor, and scale factor of the Weibull distribution (Frade and Pinho, 2002).

The present work uses a wind rotor design methodology developed by Vaz et al. (2011), considering the influence of vortices on the wake when the turbine operates at low speed ratio between the tip blade and wind speed. This model also presents a recent mathematical approach to aerodynamic optimization, based on the relationship among axial and tangential induction factors, calculated based on the blade element theory. The aerodynamic forces are found through two-dimensional airfoil data available in literature and illustrate the derivation of the general blade shape used in wind turbines.

The relevance of the work corresponds to the requirement of correct design of small wind turbines optimized from mathematical models well-known in the literature in regions that do not have electricity but they have wind potential or high wind speeds in certain parts of the year. Besides can be used for small to medium-sized wind energy installations that are isolated from a large electrical grid.

2. WIND BLADE DESIGN

2.1 Blade element theory

According to (Burton et al., 2001), the blade element theory assumed that forces on a blade element can be calculated by means of two-dimensional airfoil characteristics using an angle of attack determined from the incident resultant velocity in the cross-sectional plane of the element. The same authors complement that the velocity components at a radial position on the blade expressed in terms of the wind speed, the flow factors and the rotational speed of the rotor will determine the angle of attack.

The BET performs a discretization of the blades of wind turbine as a number of small blade elements of length *r*. BET predicts the performance of rotors considering the angle of attack, wind speed, tip speed ratio, twist angle, chord, number of blades and airfoil geometry (Singh, 2014). Fig. 1 shows the velocity diagram for a rotor blade section to a relative velocity V_R.

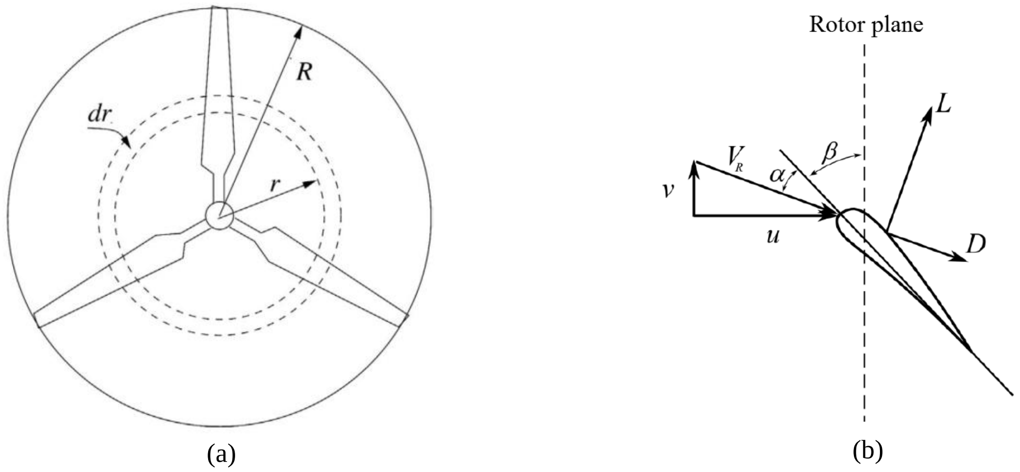


Figure 1. (a) Rotor of a three-bladed wind turbine; (b) Forces applied to the blade section.
Source: adapted from Hansen (2008).

Using the Fig. 1, the flow angle (ϕ) is obtained by the Eqs. (1) or (2):

$$\phi = \alpha + \beta \tag{1}$$

$$\tan\phi = \frac{(1-a)V_R}{(1+a')\omega r} \tag{2}$$

where α is the local angle of attack, β is the twist angle, ω is the wake angular velocity and r is the local radius of turbine.

The coefficients of normal (C_n) and tangential (C_t) forces are defined by Eqs. (3) and (4), respectively:

$$C_n = C_L \cos\phi + C_D \sin\phi \tag{3}$$

$$C_t = C_L \sin\phi - C_D \cos\phi \tag{4}$$

C_L and C_D are the lift and drag coefficients, correspondingly. Using the two-dimensional characteristics of airfoil, lift and drag coefficients of a blade element are dependent of air density, relative velocity and chord can be formulated by Eqs. (5) and (6).

$$C_L = \frac{L}{\frac{1}{2}\rho V_R^2 c} \tag{5}$$

$$C_D = \frac{D}{\frac{1}{2}\rho V_R^2 c} \tag{6}$$

The axial and the tangential induction factors are calculated by Eqs. (7) and (8):

$$a = \frac{1}{\frac{4\sin^2\phi}{\sigma C_n} + 1} \tag{7}$$

$$a' = \frac{1}{\frac{4\sin\phi\cos\phi}{\sigma C_t} - 1} \tag{8}$$

where σ is the local rotor solidity can be defined as the ratio of rotor projected area to the blades swept area (Singh, 2014). Hence, the solidity of the rotor is governed by chord length of the blade and number of blades. Local solidity of the rotor can be defined as:

$$\sigma = \frac{cB}{2\pi r} \tag{9}$$

where c is the chord, B is the number of blades and r is the local radius of turbine. The available power in a cross-section equal to the swept area A by the rotor is given by Eq. (10). Equally the power coefficient is computed by Eq. (11):

$$P = \frac{1}{2}\rho A V_R^3 \tag{10}$$

$$C_P = \frac{P}{\frac{1}{2}\rho V_R^3 A} \tag{11}$$

2.2 Prandtl's tip loss factor

The Prandtl's tip loss factor corrects the hypothesis of an infinite number of blades, since the system of vortices in the BET is different from a rotor with infinite number of blades to one with finite number (Sørensen, 2016). In this way, Prandtl formulated the correction factor F for the thrust (C_T):

$$C_T = 4\pi r^3 \rho V_0^2 \omega (1-a) a' F dr \tag{12}$$

where V_0 is the flow velocity and ω is the wake angular velocity. The factor F is calculated by relation between the ratio between the bound circulation of all the blades and the circulation of a rotor with infinite number of blades:

$$F = \frac{2}{\pi}\cos^{-1}\left[\exp\left(-\frac{B(R-r)}{2R\sin\phi}\right)\right] \tag{13}$$

which was later further simplified to (Singh, 2014):

$$F = \frac{2}{\pi}\cos^{-1}\left[\exp\left(-\frac{B(R-r)}{2r\sin\phi}\right)\right] \tag{14}$$

where B is the number of blades, R is the turbine radius and r is the radial position.

The Prandlt tip-loss factor is the most accepted correction employed and is usually taken as corresponding to a model of the flow for a finite number of blades.

2.3 Glauert's correction

Glauert (1935) proposed an empirical correction for the rotor thrust by fitting a parabola to the experimental data and it is directly proportional to axial induction factor. a_c marks as the transition point from low thrust to high thrust operation, when the axial induction factor exceeds the value of approximately 1/3, the simple moment theory breaks down. The Eq. (15) was developed, in order to consider the most general case to calculate the induction factor on the plane of the rotor, where the thrust coefficient is dependent on the induction factor in the wake.

$$C_T = \begin{cases} 4a(1-a)F; & a \le 1/3 \\ 4a\left[1-\frac{a}{2}(5-3a)\right]F; & a > 1/3 \end{cases} \tag{15}$$

According to (Wood, 2011), the Tip-Speed Ratio (TSR) controls the blade aerodynamics. Usually, TSR (Ω) ranges from 7 to 10 for a turbine operating at maximum power coefficient. The ratio is defined by Eq. (16):

$$\lambda = \frac{R\Omega}{V_0} \tag{16}$$

where R is the rotor radius and Ω the rotor angular velocity.

3. WIND CONDITIONS

The behavior of velocities in the region where the wind turbine should be installed, in particular the average speed, it is essential to estimate the energy produced, for the reason that the turbines start generating power from a wind speed starting (cut-in) and stop generating when the wind speed exceeds a safety value (cut-off).

Frade and Pinho (2002), realized a study of the wind energy potential in the coastal area of the state of Pará. For the data collection station, located in Ajuruteua beach, Bragança city, in the Northeast of state of Pará, from November 1996 to March 1999, 93.891 wind and direction speed data were collected from 30 meters height above ground. The Fig. 2 shows the average wind speed for Ajuruteua beach.

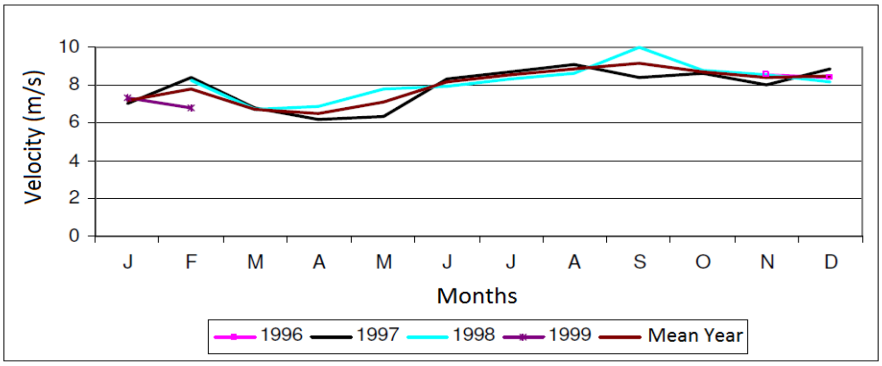


Figure 2. Velocity of the wind of Ajuruteua beach.
Source: Frade and Pinho (2002).

It was observed, that the station present annual average velocities above 8.84 m/s, the highest average velocity was registered in the month of September, 10 m/s, these conditions are sufficient for the use of wind energy by means of small, medium sized, and sometimes even large turbines.

4. METHODOLOGY

The computational code proposed by (Vaz et al., 2011) was used to design and optimize a turbine blade geometry using NACA 65_4-421 airfoil (Abbot and Von Doenhoff, 1959), the available airfoil data is often limited to the range of angle of attack. This profile was chosen because it has a high aerodynamic efficiency value for a particular angle of attack of 11.7°. Others input parameters of the turbine blade are listed in Tab. 1.

Table 1. Input data.

Parameters	Values
Rotation	300 RPM
Air density	1.18 kg/m³
Number of blades	3
Cut-in wind speed	4.5 m/s
Cut-off wind speed	12 m/s
Angle of attack	11.7º

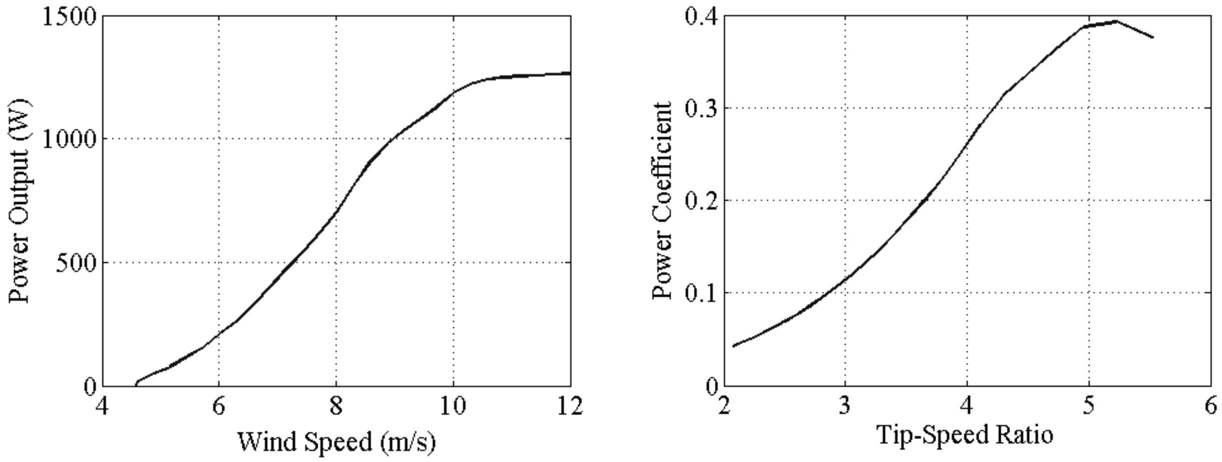
The interactive procedure for calculations of computational code used is summarized in following steps:

(i) Attribute initial values for a and a'. In this work a = 1/3 and a' = 0.001;
(ii) Calculate the flow angle of attack, Eq. (2);
(iii) Calculate the local angle of attack using Eq. (1);
(iv) Compute C_n and C_t, Eqs. (3) and (4);
(v) Calculate a and a', Eqs. (7) and (8);
(vi) If a and a' has changed more than a tolerance, go to step (ii) or else finish.
(vii) Compute the local loads on the segments of the blades and the power coefficient.

This is in principle the BET method, but in order to get good results it is necessary to apply two corrections previously presented to the algorithm.

5. RESULTS

The Fig. 4(a) shows the behavior of the output power generated by this model. The maximum rotor efficiency of a wind turbine for a given angle of attack should not be the only parameter to analyze its performance. The behavior of the power coefficient curve calculated as a relation with tip-speed ratio, should be analyzed to verify other parameters that confirm its robustness, as elucidated in Fig. 4(b).



(a) (b)

Figure 4. (a) Power output in relation to wind speed; (b) Power coefficient in relation to tip-speed ratio.

Using NACA 65_4-421 airfoil, it was possible to reach a power of approximately 1 kilowatt for recurring wind condition of the region, as shown in Fig. 4(a). When the wind speeds become more than 10 meters per second, the blade is designed to generate power above 1200 watts, thus taking advantage of the wind peaks from the seasonal wind. Regarding the power coefficient, the Fig. 4(b) shows that the optimal value of the power coefficient is 0.39 and the TSR, which is a parameter related with rated wind speed and rotor diameter, has its optimal value equal to about 5.

It should be noted that the forecast of the maximum power must meet, besides the energy demand, a correct sizing of the electric power system, because in the occurrence of strong winds, there is a tendency for the blade to experience high angles of attack, which may underestimate the maximum power generated. It can be observed in Fig. 4(b) the power coefficient as a function of the TSR, it is noteworthy that there is a strong decay of the power coefficient in relation to the increase of the TSR.

Figs. 5 and 6 show the chord and twist angle distribution along the radius for a small rotor, designed using the numerical code implemented in this work.

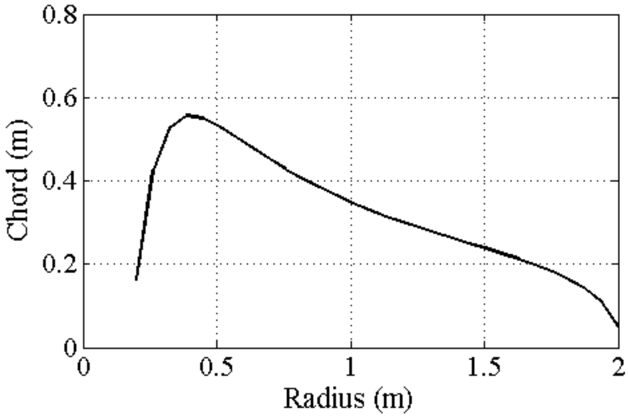


Figure 5. Chord distribution.

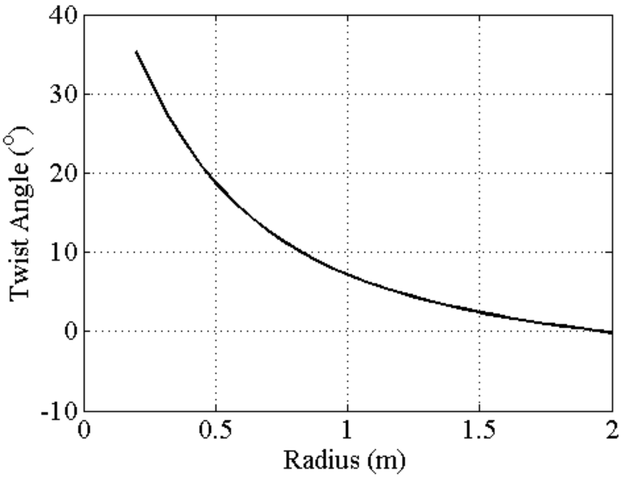


Figure 6. Twist angle distribution.

The width of the wind turbine blade at a given distance along the length of the blade, *c*, has a decreasing until the blade tip as well as the twist angle.

The aerodynamic parameters for determining the blade shown in Fig. 7 were obtained using the profile NACA 65_4-421.

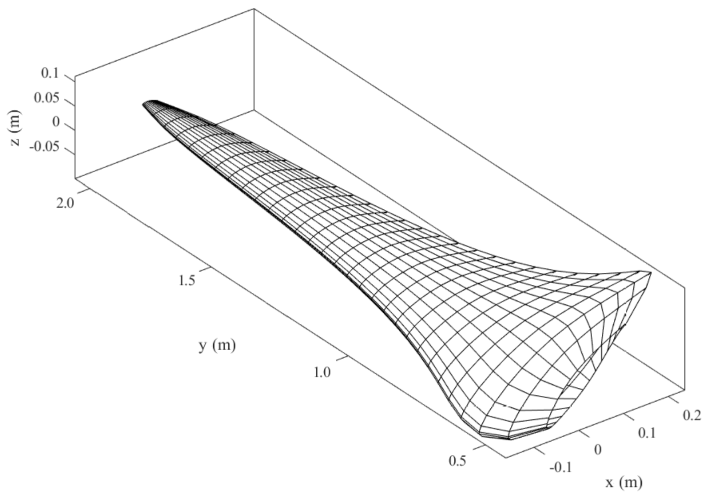


Figure 7. Chord and twist distributions.

It is also noteworthy that the shape of the blade generated has little twist, facilitating the production of the pieces, with a wingspan of 2 m. The shape of the blade generated consists of sections of different widths, thickness and twist angle along the blade. The blade's performance in relation to lift and drag sets the exact angle of attack of 11.7 ° for satisfactory performance in low wind conditions.

When the rotor of a wind turbine employing the blade of Fig. 7, working at high wind speeds, will lose lift quickly, avoiding entering a working configuration that could damage the electrical system.

For best performance it has been configured that this turbine rotor has three blades. Although one blade is the ideal number due to reduced drag, the turbine would be unstable, making it an unviable option, while two blades are more prone to a gyroscopic precession phenomenon, causing instability than three-bladed turbines. For this reason, we chose to design the three-bladed turbine rotor as they provide satisfactory energy efficiency, stability and durability.

6. CONCLUSIONS

An approach for optimization of horizontal-axis wind turbine blades design using the BET theory and some empirical corrections was presented. The mathematical model obtainable is an excellent alternative for the design of more efficient wind rotors, the main improvement comes from its mathematical structure, which takes into account the relation to the axial and the tangential induction factors.

The results obtained in this work present a consistent behavior, for instance, when the rotor operates at rated speed, there is a production greater than 800 W. On the other hand, when the wind condition reaches values greater than 10.5 m/s, the generated energy approaches 1.2 kW, remaining constant until the condition cut-off. Thus the design of a wind turbine blade to generate energy in low wind conditions using blade element theory is applicable, demonstrating that it is possible to use this type of technology for small scale energy production as in the Amazon region.

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