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STUDY OF APPLICATION OF COMPOSITE MATERIALS FOR HORIZONTAL AXIS WIND TURBINE BLADES[1]

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Abstract
The most common material used for manufacturing blades for horizontal axis wind turbines is the fiberglass-reinforced polymer (FRP), or just fiberglass. The production aims to combine high performance with reduced cost in material and manufacturing process. While the low specific weight of a blade made of fiberglass can help in starting up, in a farm system under weak winds it may leads to reduced torque situations. Thus a large amount of variation in angular velocity and therefore on the specific velocity of the system could happens. Since the specific velocity is directly related to the coefficient of power, *Cp,* of a wind rotor, this article presents a study considering composite materials and appropriate geometries, designed to maximize the rotation of a small rotor (with fixed pitch angle) by virtual simulation with finite elements.

Key words: wind energy, composite materials, finite elements

ESTUDO DE APLICAÇÃO DE MATERIAIS COMPOSITOS PARA AS PÁS DE TURBINA EÓLICA DE EIXO

Resumo
O material mais utilizado para fabricação de pás para aerogeradores atualmente é o plástico reforçado com fibra de vidro, ou simplesmente fibra de vidro, onde sua produção procura aliar alto desempenho com reduzido custo no material e no processo de fabricação. Ao passo que o baixo peso específico de uma pá em fibra de vidro pode auxiliar no arranque de um sistema eólico em regime de ventos fracos, seu torque será reduzido. Isso significa que uma grande quantidade de variação na velocidade angular e conseqüentemente na velocidade específica do sistema poderia acontecer. Estando essa velocidade específica diretamente relacionada com o coeficiente de potência, *Cp,* de um rotor eólico, este artigo apresenta um estudo com materiais compósitos projetados com objetivo de maximizar o giro do rotor de pequeno porte (com ângulo de passo fixo) através de simulação virtual por elementos finitos.

Palavras-chave: energia eólica, materiais compósitos, elementos finitos

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1 INTRODUCTION

The removal of wind energy conversion to electricity requires a set to interact with wind. Turbines are machines intermediate made to capture the wind and further processing into electrical energy.

Wind rotor is formed by a set of solid pieces made to allow an amount of spin considered great for transferring an electric generator. A transfer is made by turning a shaft and, in some cases, increased with the aid of a set of gears.

The blades, that are part of this set of pieces, are elements that come into direct contact with the air flow. The moment of interaction of the blades with the wind is when kinetic energy is transferred to the surface of the blade.

The design of the blades is done in order to maximize this energy transfer and transform most power.

Several variables are present when determining a geometry which requires controlled behavior during the contact with the fluid. According to Burton *et al* (2001) to obtain an efficient design of the blades, some goals must be met:

- maximize energy production for a specific distribution of wind;
- seek the maximum power limit;
- resistance loads inherent to the object and the fatigue that can occur;
- the tendency to restrict movement of the tip of the blade toward the tower;
- avoid resonances;
- minimize weight and cost.

2 MATERIAL AND METHODS

The design of the rotor blades must take into account structural and aerodynamic aspects. Within the scope streamlined, it can be listed some stages of project:

a) definition of the diameter of the rotor;
b) definition of the geometry of the airfoil;
c) definition of the aerodynamic parameters (pitch angle, speed);
d) definition of the geometry of the longitudinal profile of the blade (longitudinal twisting);

a) Diameter of the rotor

The rotor is formed by the parties that allow the rotation of the shaft transmit spin to the generator. The blades are the main elements that form the rotor. The diameter of the rotor is directly related to the performance of the turbine. This relationship is presented in Eq. 1

$$P_{dis} = \frac{1}{2}\rho A v^3 \qquad (1)$$

Where the wind power available, P_{dis}, is directly proportional to air density, ρ, the area swept by the rotation of the blades, A, and the cube of wind speed, v.

Thus, the length of the blade is defined by the power wanted remove the air and converts into electricity.

b) Geometry of the airfoil

There are several airfoils designed for use in wind turbines. However most of these projects are originated from the wings of aircraft.

This research defined the lift coefficient *Cl* as the main measure of efficiency of the profile to be chosen. The drag coefficient, *Cd*, was also considered in the analysis, as in the case of a small rotor the goal is to "find" a satisfactory ratio between lift and drag to control the speed, resulting from angular velocity and wind speed.

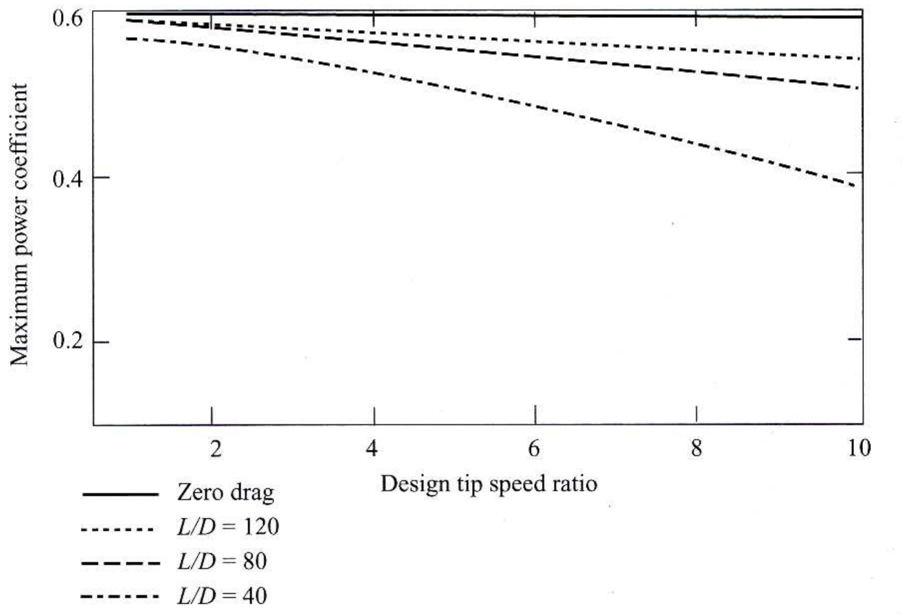

Figure 1. Lift (*L*) and drag (*D*) on the coefficient of power and speed specific
Source: Burton et al (2001)

As shown in Fig. 1 the more increases the specific speed (tip speed ratio), more is needed to have a design that leverages the lift (*L*).

The profile analysis was conducted with the aid of the software *JavaFoil*, available on the website of Professor Dr. Martin Hepperle, University of Stuttgart, Germany. This software was developed in *Java* language and has its main use in analysis of profiles of wings for aircraft models. Some concepts of aerodynamics applied to airfoils of aircraft wings can be applied to analysis of blades for wind turbines.

The profile initially chosen was the MH110, also developed by Martin Hepperle. This airfoil is drawn from the coordinate points in two dimensions (x and y axes).

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After entering the coordinates, it is possible to visualize the shape of the airfoil (Fig. 2).

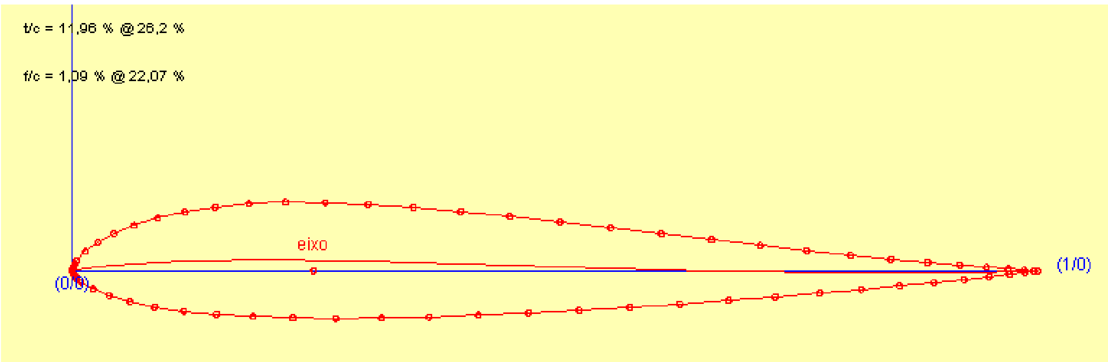

Figure 2. Form the airfoil MH110

This profile was created from 68 points in Cartesian coordinates. The maximum thickness (*t/c*) of the profile is 11.959% and 26.2% of the x-axis. The curvature (*f/c*), which is the curve between the top and bottom edge of the profile has the maximum value of 1.088% to 22.7% of the x-axis.

With the airfoil created, it is possible to determine which angle of the profile will have more lift, drag and pressure (in this case, wind power). To analyze wing aircraft, the angle of attack is directly linked to the variables listed above, as the aircraft wing is interacting only with one wind direction, i.e., the calculation is done by shifting the wing and not by the displacement of fluid (wind).

In the case of the wind rotor, there are two components to consider: the wind and rotation. From a speed that is the result of a geometric sum of these two speeds it can be determined the angle of attack. Thus the angle of attack of blades for wind turbines is not constant as in airplane wings. What it has is the fixed pitch angle. Therefore it is clear the importance of the adequacy of the design of the blades to arrive at an angle of attack such that achieve the greater lift.

c) Aerodynamic parameters

From profile MH110 set, the results of different rates of lift for different angles of attack can be analyzed. Table 1 shows the lift, drag and pressure for angles of attack from 0 to 11 degrees, with an increase of 1 degree.

Table 1: parameters according to the angle of attack

α [°]	*Cl* [-]	*Cd* [-]
0,0	0,017	0,02460
1,0	0,103	0,02491
2,0	0,223	0,02422
3,0	0,343	0,02328
4,0	0,462	0,02500
5,0	0,581	0,02667
6,0	0,676	0,02644
7,0	0,769	0,02677
8,0	0,856	0,02876
9,0	0,923	0,03577
10,0	0,977	0,04411

Table 1 shows that the highest value of *Cl* is to angle of attack 10° but the optimal lift-drag ratio is when α=8°. Whereas the blade is designed for a wind speed pre-determined, it can be calculated the speed and therefore the resulting velocity. With the resulting velocity known, it is possible to draw the blade pitch angle (which is fixed) such as to reach the desired angle of attack, because it can be found with the subtraction of the angle between the resulting velocity and Vr plane of rotation and the pitch angle.

According to Carvalho (2003), there is a specific velocity represented in Eq. (2) by λ. This parameter, which is a dimensionless number, is given by the relationship between the speed at the tip of blade v_u and the velocity v of the wind.

$$\lambda = \frac{v_u}{v} \tag{2}$$

The speed of rotation v_u can be defined by the product of angular velocity ω of the blade and its radius R as shown in Eq. (3).

$$v_u = \omega R \tag{3}$$

For Burton *et al* (2001), a specific speed $\lambda = 6$ is suitable for three-bladed rotor. Whereas the wind speed is v =10m/s, the rotation speed is 60m/s for a 1 meter radius rotor. The rotor in this configuration will work approximately at *573RPM*.

d) Geometry of the longitudinal blade profile

Longitudinal blade profile has a twist to increase their performance. For Gasch and Twele (2002), to define the chord of the blade it is necessary to solve Eq. 4, even when c_L and λ are constants.

$$c(r) = \frac{2\pi R}{n} \cdot \frac{8}{9} \cdot \frac{1}{c_L \lambda_D^2 \frac{r}{R}} \tag{4}$$

Where

c - blade chord

R - radio of rotor

n - number of blades

c_L - lift coefficient

λ_D - tip speed ratio of design blade geometry

r - local radio

Solving the Eq. (4) for nine sections of the blade, it is possible to have the measures of the chord at these points, as shown in Fig. 3a.

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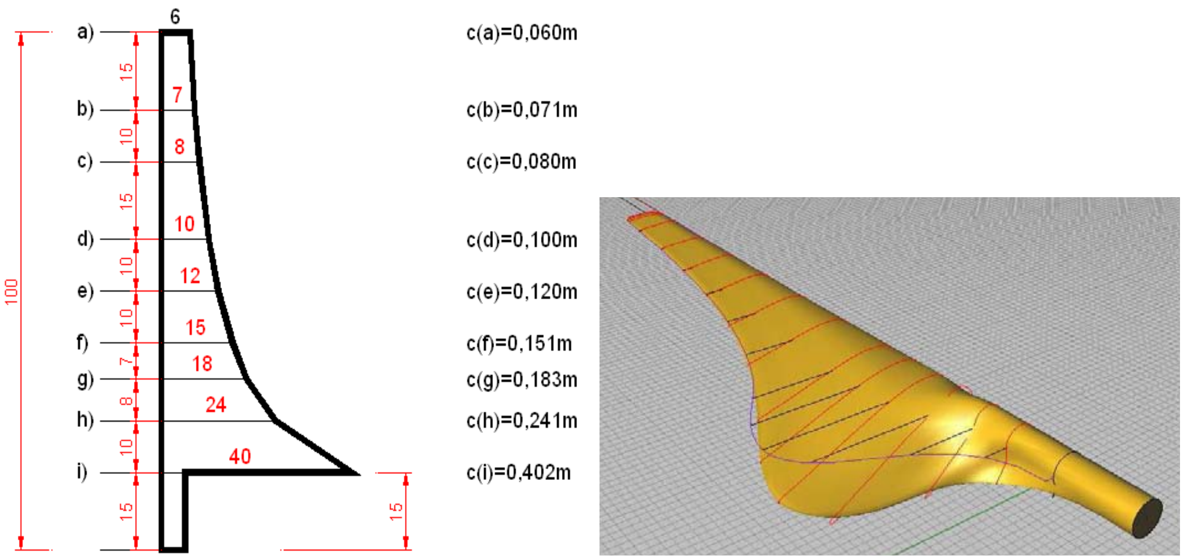

a) b)

Figure 3. a) Dimensions of the blade chord for the defined sections, b) 3d model of the blade

Also according to Gasch and Twele (2002), the twist of the blade can be defined as in Eqs. (5) and (6)

$$\beta(r) = \gamma(r) + \alpha_A(r) \tag{5}$$

$$\gamma(r) = \arctan\left(\frac{3}{2}\frac{r}{R}\lambda_D\right) \tag{6}$$

where γ represents the angle between the relative velocity of the wind (geometric sum between wind and the speed of rotation of blade) and the rotation speed of the blade. The α is the angle of attack.

Adopting this construction method of the blade geometry, it is possible to model the blade in three dimensions (Fig. 3b) with the aid of the software Rhino3D from Robert McNeel & Associates.

In order to transfer the ideal model (Fig. 3a) for the 3d model (Fig. 3b), the blade get some smooth to make manufacturing in composite material easier.

To perform simulations, software Abaqus/CAE 6.8 (2008) was used. The material chosen for the blades is laminar with an elastic behavior, where it can have layers with different orientations for the fibers. The matrix is epoxy and fiberglass are type E. Thus it is considered the following elastic properties for fiberglass with epoxy matrix: $E_1 = 45$ *GPa;* $E_2 = 12$ *GPa;* $G_{12} = G_{13} = G_{23} = 5.5$ *GPa;* $\nu = 0{,}19$.

After determining the material properties used in the simulation, was created the section Shell homogeneous for the blade. Blade has three layers each one with *3mm* of thickness.

Considering the small size of the rotor (*Ø~2.00m*), the structural aspects reported in this research are:

- Mechanical strength of the blade due to:
    - constant wind load (average)

- cross load wind
- load of greater turbulence in the wind
- centrifugal force
- self-weight
- gyroscopic force

- Project material blade

2.1 Mechanical strength

Loads acting on the blade due to the interaction with the air flow are uniform aerodynamic forces. Assuming that apparent speed v_w (resulting velocity) is constant, there is a distribution of forces on the blade when it is operating. This distribution occurs in two ways: thrust (Eq. 7) and rotational force (Eq. 8), were ρ represents the air density considered 1.29 kg/m³ at sea level and dr is the component that represents the infinitesimal thickness ring considered for calculating the swept area of the blade, where there will be the interaction of rotational speed and the wind.

$$dT = \frac{1}{n}\left(\frac{8}{9}\frac{\rho}{2}v_w^2\right)2\pi r dr \quad (7)$$

$$dU = \frac{2\pi R}{n\lambda_D}\left(\frac{16}{27}\frac{\rho}{2}v_w^2\right)dr \quad (8)$$

There is also forces due to the gusts, causing variation in dT and high instantaneous pressure in the blade, however if the thrust is calculated with the resulting velocity considering wind speed and rotational speed high, it can be considered that the thrust is calculated to have gusts of wind.

Forces due to yaw, gyroscopic and coriolis were disregarded because this movement is usually slow in relation to rotation of the blades. The inertia due to the braking system was also disregarded because the rotor has no mechanical brake.

According to Gasch and Twele (2002), for large turbines, the blade weight influences a cyclic loading. For rotors with Ø = *20m*, the influence is little, for rotors with Ø *<5m*, this load is irrelevant.

2.2 Material of the blades

Polymers reinforced with glass fiber composite materials are produced primarily from the agglomeration of thin flexible strands of glass with polyester resin (or other type of resin) and subsequent application of a substance polymerization catalyst. The plastic reinforced with fiberglass - PRF has high tensile strength, flexural and impact, and much used in structural applications. It is lightweight and allows great flexibility in design, allowing the molding of complex parts, large or small, seamless and highly functional and aesthetic value.

Different volume fractions give different performance in products manufactured in PRF (volume of components: *Vfibers - Vmatrix – Vvoids*). According to Neto and

Pardini (2006), the volume of voids – *Vvoids* must be <1% for not harm the mechanical performance of the polymer.

Matrix forms the continuous phase of the composite and plays the role of uniting ribs and distributing or transfering loads or stresses.

The selection of the matrix takes into account the needs of the composite project, such as recyclability, the fracture toughness among others.

Resin matrix polymers can be based on epoxy, polyester, phenol and so on. There are two major groups of matrix for PRF: thermosetting and thermoplastic.

The thermosetting are the most used. These resins form a viscous liquid that solidifies by chemical reaction exothermic polymerization or cure. Natural healing is slow due to the low mobility of the molecules of unsaturated polyester. This problem can be solved by the addition of catalysts, where free radicals attack the instauration polyester, initiating the PCR, forming a thermosetting network. The catalyst most commonly used is methyl ethyl ketone, or simply MEKP.

There are four groups of thermosetting matrix:

- orthophthalic: use in crafts, simple materials;
- terephthalic: laminate reinforcement fibers;
- isophthalic: gel coat for exterior finishes;
- bisphenolic: parts in the aggressive site and high temperature.

Thermoplastics also serve as a matrix, however are less used in the manufacture of low cost. This type of material has higher fracture toughness, better impact resistance, and is likely to be recycled. This factor can be an indicator in the selection of material in relation to what is not presented as feature recyclability.

Matrix for PRF products can still be made by ceramic materials, carbonaceous materials or metallic materials. All of these products are use with specific requirements.

The composition of the glass may vary, determining some important aspects for selecting this material. S-glass, for example, shows an amount of aluminum oxide that it's double than found in E-glass, it also has three times more magnesium oxide than the same glass type E. However the cost of a kilogram of S-glass can be eight times higher than type E. Whereas the tensile strength of S-glass reaches *2.80 GPa* and E-glass reaches *2.40 GPa*. It can be conclude that the difference in value is too high in relation to the difference in structural performance. This relationship shows a more determining factor for selecting the type of glass fiber to be used in manufacture products.

3 RESULTS AND DISCUSSION

Calculating the aerodynamic loads, solving Eq. (7), it results *2226.063 N* thrust distributed with non-linear variation, increasing along the radius of the blade. The rotational force was calculated with Eq. (8) and has magnitude of *494.68 N* increasing linearly along the radius.

Figure 4 shows in a) sequence of lamination [0,0,0] , and b) [0,10,25] respectively.

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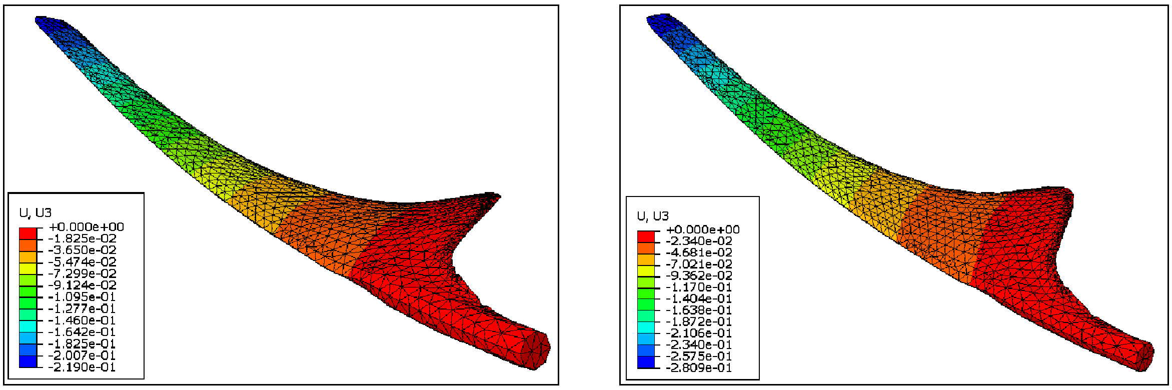

a) b)

Figure 4. Displacement of blade tip a) lamination 0 degree, b) lamination sequence 0-10-25 degrees

Figure 5 presents the distribution of von Mises stresses in the blade and shows that the major loads occurs in the area near to the part that is fixed to the shaft. This simulation shows where the material must be reinforced increasing thickness of the shell or use a piece of structural steel to make the junction of the blade shaft.

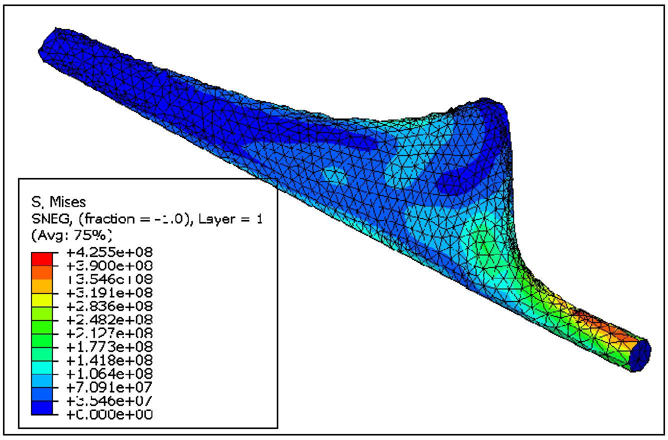

Figure 5. von Mise Strains

Simulations by finite element method obtained suitable results for a blade shaped virtually in 3D. The loads were determined for the object's interaction with the wind and rotation at high speed, in the range of *573 RPM*.

For both laminated tested, the one that best fited the project is considered the one with no change in the angle of the layers. Due to the efforts of bending moment over the blade, this lamination sequence leads to smaller deflections.

The largest tip blade displacement was no more than *22cm*. For this setting becomes appropriate design the distance between the blades and tower larger than *22cm*.

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The highest stresses were observed at the root of the blade, indicating that the profile MH110 chosen in addition to having a good lift coefficient resists well to the loads of operation.

This is a preliminar study, further analysis will be conducted to define the shell thickness being used, considering other factors such as the limits of material failure.

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