STUDY OF A SMALL WIND GENERATOR FOR RESIDENTIAL USAGE

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Abstract. *The utilization of wind energy is in evidence because it has several benefits not only for who extracts or uses it, but also for the environment. The projects of big wind turbines are very known as well as the great number of wind farms, usually with purpose of commercial exploration of electric power. Data from the International Renewable Energy report of 2005 showed that the capacity of electricity generating by global winds exceeded 50 GW. In 2007, Brazil produced 247 MW of wind energy. This energy comes from power plants located mainly in the Brazilian coast. The Atlas of the Brazilian Wind Potential, published by the Reference Center for Solar Energy and Wind - CRESESB / CEPEL presents a study which states that the country's wind energy potential is of the order of 143 GW. The use of the wind as an energy source in isolated cells, as residences for example, in urban areas can represent a considerable economy on electricity account. The computational technology can be applied in project development in many ways like the definition of favorable location areas for wind farms or the executive project of the aerogenerators. It is possible to conduct geometric modeling, numerical simulations for structural analysis and test simulations in a virtual environment. In these terms the present article describes the context of using of wind energy and, in summary form, a possible solution for electric power generation for residential usage, describing a project for a small equipment. This work also represents the beginning of a research to indicate whether it is possible to design a rotor with minimal equipment and maximum performance, conducting tests and structural simulations using CAE technology.*

Keywords*: Wind energy, renewable energy, energy generation*

1. INTRODUCTION

Electric energy is extracted through sources known as renewable and also through sources known as non renewable. For instance, petroleum and its by-products can be classified as sources of non renewable energy. On the other hand, solar and wind energies are considered renewable, clean and ecological.

The extraction of energy from the sun and wind are practices that tend to minimize the emission of pollutant in the atmosphere because they do not request combustion processes.

The growth in using of renewable energy sources is strongly benefited by the technological development that pursues to increase the efficiency of equipments and facilities.

In an attempt to reach higher project efficiency, professional from different technological background as electrical engineering, mechanical engineering and industrial design developed quite daring projects. Aero generators of vertical and horizontal axes having several shapes and sizes, alternators with step control, safety devices as active aerodynamic brakes among others items that could be cited, are present in scientific papers, thesis, dissertations, books and news published by the press.

The transformation of wind energy in electric energy can be discussed under many aspects. To delimit the scope of this work, the following sections emphasizing the rotor design and computational structural analysis for a small size aero generator and are presented as follow

- Energy generation and renewable sources;
- Wind energy;
- Aerogenerators models;
- Design and computational structural analysis of a small size rotor;
- Results and final considerations.

2. ASPECTS OF ENERGY GENERATION AND THE RENEWABLE SOURCES

Since the beginning of civilizations the mankind is extracting from the nature forms of energy for his profit. From a biological point of view, it can be said that the most basic need of a creature is to get and store energy to maintain their bodies in operation. According to Rosim (2008), energy is fundamental for a nation development as well as for the maintenance of the life.

Along his technological development the mankind learned some methods to control the availability of energy in the nature. Firstly with the discovery and the domain of the fire that represented a milestone in the man's domain over the natural forces. After with the domestication of animals it was possible to develop means of transport and new methods for farms handling. So the man gained some freedom from the intrinsic aleatority of nature energy availability.

The increase of the world population together with the capitalist production of the XVIII century culminated in the Industrial Revolution. Then the energy from non renewable sources assumed a fundamental role in the substitution of the human and animal workforce by the machine force.

The fossil fuels (derived from petroleum and mineral coal), as well those extracted from biomass or even the nuclear sources are used for power supply for machines and also for electric energy generation.

Ennio's diagram, as shown in figure 1, classifies the energy source in two categories: renewable and non renewable. For Ignácio (2007) there are three primary energy sources: solar, geothermic and gravitational. All these sources are considered renewable. There still are the so called secondary renewable energy sources: energy from the oceans, eolic, hydraulic and biomass energy. Using Ennio's diagram, Ignácio (2007) classifies the nuclear energy as a primary source non renewable and considers the petroleum by-products, natural gas, mineral coal, peat and schist (all being biomass by-products) as secondary non renewable sources of energy.

2.1. Biomass energy

Biomass is an organic material considered as energy source and can be found as solid, liquid and gas. Combustion is the process used to extract energy from biomass. The heat generated from combustion is used to boil water and the steam so produced is conducted to drive turbines. The turbine movement is transformed in electric energy via a generator. The combustion process releases carbon dioxide and this is a serious problem from the environmental point of view.

Biomass gasification is the process where the solid organic material is converted into gaseous fuel by biologic degradation of residues like urban or rural garbage. Among the products extracted in this process are hydrogen, carbon monoxide and carbon dioxide. These gases are also used for the chemical industry.

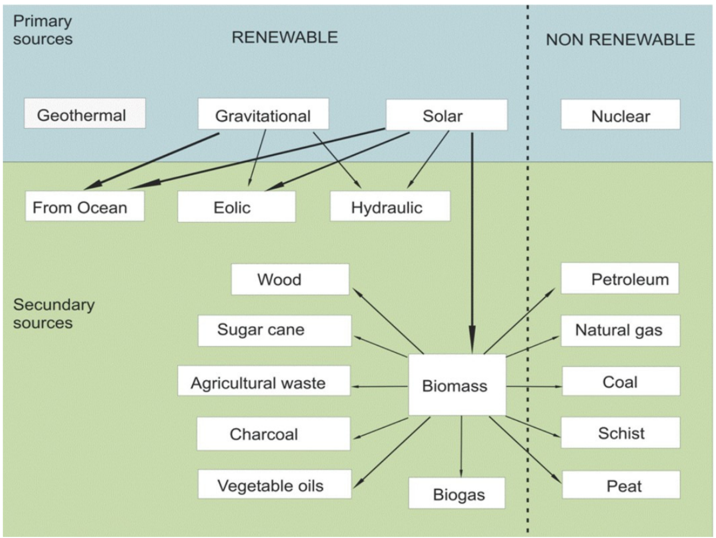


Figure 1. Ennio's diagram – energy source
source: http://www.eca.usp.br/njr/voxscientiae/ercio_ignacio_38.htm

The production of bio-oils through the pyrolysis[1] process, the conversion of sugar for sugar-cane into ethanol through the action of bacteria, the oil extraction from the castor oil plant and from the soy are examples of biomass usage as liquid substances and by-products of the fermentation. Alcohol fuel and biodiesel are energy sources largely used in Brazil. According to ANP (National Petroleum Agency), the Brazilian production of biodiesel was something like 176 million liters in 2008.

2.2. Energy from fossil fuels

Fossil fuel is the result from the long decomposition process of plants and animals under extreme high pressure and temperature over millions of year.

Petroleum is the fossil fuel most consumed by man. However there are other two carbon compounds that are used for energy production: natural gas and mineral coal.

[1] Pyrolysis is a process of burning of biomass; usually wood, to break the molecular structure of the material, usually in the absence of air, obtaining the gas and acid by-products suitable for production of methanol, acetone and other acids.

Fossil fuels are among the so called non renewable fuels, although they are geologically always being produced by nature, their extraction rate is higher than the Earth capacity to generate compound for their formation.

Energy production through fossil fuels is made mainly by thermoelectric power plants. These power plants are highly pollutant, sending tons of pollutant gases in the atmosphere.

2.3. Nuclear energy

Nuclear energy can be obtained through two processes: atomic nucleus fission or fusion. In the fission process, the atomic nucleus releases energy when it is split in two or more parts. In the fusion process two atomic nucleuses are joined to form a new one releasing energy in this union phenomenon.

As others forms of electric energy production, nuclear fission or fusion generates heat that is used to make steam from water and the steam drives a turbine coupled to a generator.

Nuclear fission has some advantages, including non emissions of gases in the atmosphere as it occurs when burning fossil fuels. However with the nuclear fusion the risks are quite considerable. A major problem is the release of radioactivity. This phenomenon tends to cause damage to living beings. Diseases such as cancer or even genetic mutations are among the negative aspects of the use of radioactive substances.

2.4. Energy from alternative fuels

Alternative energy sources can be considered as possible solutions for shortage crises of conventional fuels. Among the sources considered as alternative are the solar energy, wind energy, the tide power, the geothermal and the hydrogen fuel cells.

Solar energy can be divided into photovoltaic and thermo solar. Photovoltaic energy is extracted by the direct conversion of sunlight into electricity. In 1839 the French physicist Edmond Becquerel discovered that the absorption of sunlight produces a difference of potential at the extremes of a semiconductor material structure. This structure is called photovoltaic cell. The thermo solar energy works with the collection of the sunlight through solar panels and is used mainly to heat water.

Wind energy is captured by devices called aerogenerators, which transforms the kinetic energy of wind into electricity. This type of power generation will be treated in more depth in the course of this work.

Tidal power is the generation of energy through two ways: the movement of the tidal flow, used to move locks in the vertical direction, creating a potential energy by the difference in height, and the kinetic energy generated by currents due to tides also. In both cases, energy is directed to turbines that generate electricity. The tidal power is an excellent "inexhaustible" energy source, though their cost of deployment is very high, which makes unfeasible its usage in large scale.

Geothermal energy is also an abundant source to be exploited. Our planet is composed of layers. The layer below the earth's crust is a mantle made of rock in a liquid phase, called magma. In these areas there are deposits or currents of water with high temperatures. To generate electricity power plants are established where there are geothermal deposits. These plants typically extract the steam from the layers below the earth crust and make the conversion to electricity through specific turbines.

Hydrogen cells are used for storage and transport of energy. For the hydrogen becomes an energy source, it needs to be isolated. This requires more energy than the hydrogen can offer, so this is a non-sustainable source.

3. WIND ENERGY

Wind is a mass of air that gets kinetic energy by the pressure difference from one region to another. It can be said that wind becomes from solar energy, because the difference in pressure is given by the difference in temperature of the Earth surface or of water surface.

According to the Brazilian Center for Wind Energy, there are currently more than 30,000 wind turbines in operation worldwide, totaling 13,500 MW of installed nameplate capacity.

The generation on a large scale or in the Megawatt scale has shown its benefits. But for the domestic power generation some barriers such as lack of interest in implementing specific projects make unfeasible the mass production as well a large distribution of residential models of aerogenerators. There are companies qualified for this production, but the massive use of wind energy is quite far from reality.

4. AEROGENERATORS MODELS

The most common models in the literature are the VAWT (Vertical Axis Wind Turbine), Darrieus, Savonius and Reel (Figure 2) and the weather vanes of horizontal axis HAWT (Horizontal Axis Wind Turbine) with great diversity of design.

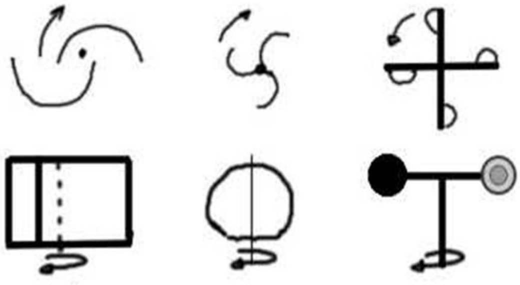


Figure. Models of rotor with vertical axis
Source: Panel presentation of Mafalda Antunes, Department of Industrial Electronics - University of Minho, Portugal, 2003

According to Acioli (1994), vertical axis rotors have by definition high torque and low speed, being ideal for heavy work such as hauling water or grinding grain. For Garcia, Simioni and Alé (2006) the advantages of models VAWT are not associated with need for control systems for the direction of the turbine in the main flow as well as aspects of construction and maintenance, since the generators are at soil.

Savonius model, invented by the Finnish engineer Sigurd J. Savonius in 1922, is a VAWT consisted of two blades in the form of shells placed side by side in contrary positions and connected to a vertical axis. These turbines are driven primarily by forces of drag and have high torque and low speed of rotation.

The Darrieus turbine, developed in 1931 by French G. J. M. Darrieus, is a model that has two or three blades in the Catenary[2]. According to Garcia, Simioni and Alé (2006), these machines have weaknesses in the starting, being necessary to auxiliary motor to help in the starting.

As the power in wind generators is obtained by a device that converts rotation into electrical power, equipment with higher speed of rotation are the most suitable.

The horizontal axis turbines of medium and large size have advantages in relation to VAWT. These models are currently the most used in the generation of electric power connected to power grids.

A wind generator HAWT has three main parts: rotor, generator and tower.

The rotor consists of the blade, shaft and gears to transmit the rotation to the generator. The blades of a horizontal axis rotor are objects of study in aerodynamics to optimize its use. In numbers one, two, three, four or more, the blades act as a barrier for generation of circular motion around an axis. They interact directly with the forces of wind and need specific design, appropriate materials and safety systems.

Most used nowadays are the HAWT of three blades (Figure 5), usually made of fiberglass and with the tips painted in red to inhibit the presence of birds. Also have systems of aerodynamic and mechanical brakes, activated when the wind becomes quite strong.

Figure 3. Modern aerogenerators with horizontal axis
Source: http://www.energiasrenovaveis.com/images/upload/per0080_1.jpg

[2] In mathematics the catenary describes a flat curve similar to that would be generated by a rope suspended by its ends and subjected to action of gravity.

The area covered by the circular motion of the blades defines how much power the generator will provide, as shown in Figure 4. So the energy is directly linked to the size and angle of twist about the longitudinal axis of the blade (angle of attack).

A system of gears of different sizes increases the spin and transfers the rotational motion to the generator, which acts as a dynamo or automobile alternator.

Generators, or electro-mechanical converting equipments, enters into the system with two possible purposes: to send energy to power grid, usually as a secondary alternative to the existing network, or to charge batteries for various uses.

Height of the rotor is directly related to wind conditions of the site. The higher is the rotor, more the wind will reach it. This fact raises concern about the structure of the equipment. The tower of support should be calculated according to the load exerted by the suspended parts and especially the wind force that it will endure (horizontal load), and the vibration caused by movement of the blades.

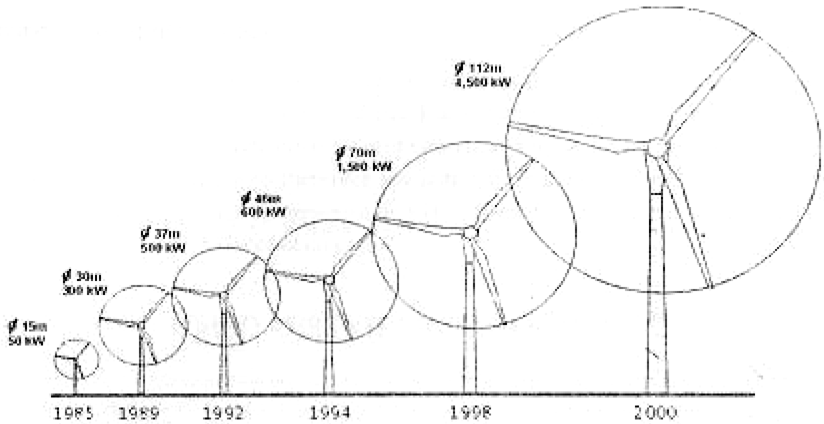


Figure 4. Evolution of size and power of aerogenerators
Source: Kuik apud Tolmasquim, 2003, p. 216.

4.1. Parts of aerogenerators

According to Tolmasquim (2003) a wind system should provide a higher final yield working in harmony. For this operation, most of the generators of medium and large have a rotor, a multiplier box, an electric generator, control and guidance mechanisms and a support tower. For Tolmasquim (2003) the rotor is responsible for transforming the kinetic energy of wind into mechanical energy of rotation of a shaft. The multiplier box or transmission is responsible for transmitting energy to a generator. Usually this transmission tends to increase the spin speed, thus increasing the power for the generator, which converts the rotation into electricity. The control and direction mechanisms direct the rotor and control the speed of the blades. The support of all these components is made by the tower, which have suitable height for each region considering the wind conditions.

5. DESIGN AND STRUCTURAL ANALYSIS OF A SMALL SIZE ROTOR

For producing a three dimension rotor model, a drawing supported by computational technologies was developed with the following objectives:

1. Modeling in a three dimensional environment an horizontal rotor with three blades, three yoke plates (an yoke plate is the connection piece between one blade and the rotor shaft), two bearings, cylindrical beam and tip cone.
2. Analyzing in summary form the influence of wind forces on the modeled blades taking into account the blade angle of attack.
3. To put in evidence the computational support for design this type of equipment.

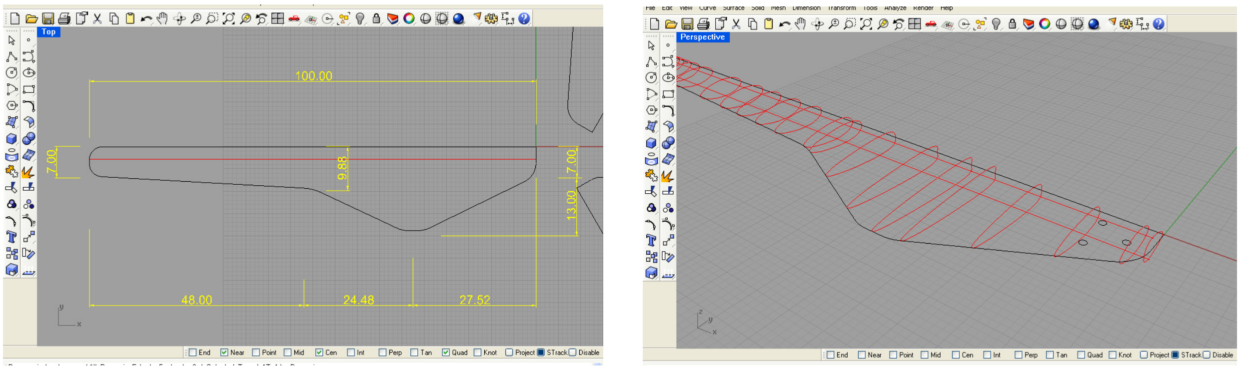
The adopted CAD software was Rhinoceros 3d from Robert McNeel & Associat. Rhinoceros works with NURBS (Non Uniform Rational B-spline) objects. The adopted CAE software was Abaqus from Simulia.

The rotor being designed is a HAWT (Horizontal Axis Wind Turbine) rotor.

The blade top view was generated (fig. 5a) and also the front and right views with only lines and dimensions (two dimensional drawing). From this moment it is possible to start the elements assembling in three dimensions.

Lines along the blade span and parallel to the xy plan were created: one having an elevation of 1.50cm (equivalent to state z = 1,5cm) and other having an elevation of -1.5cm (equivalent to state z = -1,5cm)

These lines were created to serve as auxiliary lines for the command *cross-section profiles.* This command produces cross sections through the auxiliary lines and the lines that define the object edge. Figure 5b shows the cross sections (in red) with the definitive shape and the separation between each two of them.



a) b)

Figure 5. a) Top view of one blade. b) Construction lines for modeling the blade surface shape. Dimensions are in centimeters.

The blade surface is created with the command *loft* that joints the construction lines previously created through an imaginary rail. With the blade surface available for visualization it is possible to make reflections concerning constructive technical aspects.

Figures 6 show as the yoke plates were drawn: auxiliary solids (in green) were used to make subtractions and reach the desired shape. On each yoke plate three holes were created to permit the passage of fastens bolts. The diameter of each hole is 1 cm. To help the drawing work, a disk was drawn with its axis aligned with the rotor axis and mid intersected by the xy plane; the disk is represented in red on figure 7a and 7b. This disk does not represent any part of the rotor. Three blades were equally disposed around the edge of the disc, i.e., each blade is 120° apart from the others two blades.

According to Carvalho (2003), the triple blade configuration has the biggest market share. These rotors are submitted to lower mechanical stresses and have acceptable noise emission levels.

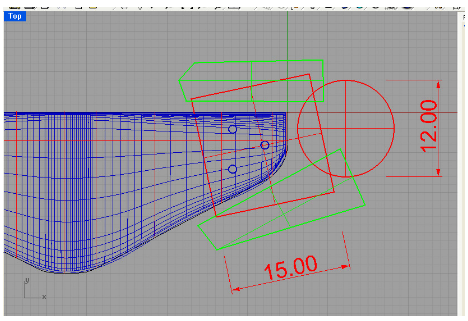


Figure 6. Dimensions of connection of the blade support with the cylinder

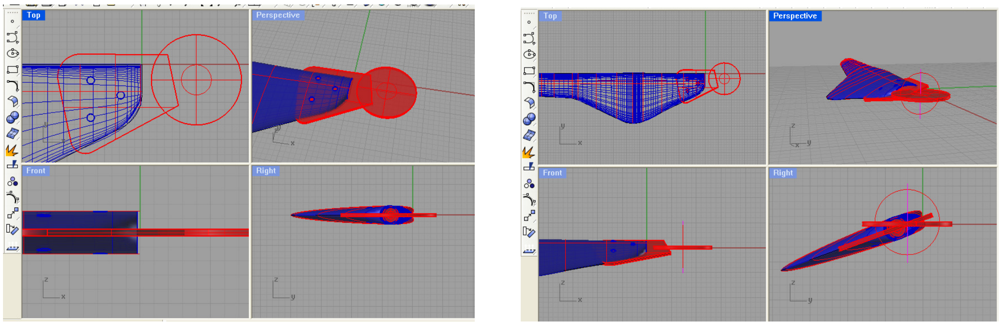
The blade angle of attack is defined as the angle between the symmetrical line of one blade cross section and the blade plane of rotation. This angle was defined to be 70° (bottom right drawing in figure 7b).

Many aerodynamic characteristics of one blade are defined by the blade angle of attack and the whole efficiency of an aero generator is strongly tied with the aerodynamic characteristics of the blades.

The rotor shaft has a tube shape (fig 8a). In his interior two radial bearings are fitted (fig 8b). One cylindrical beam rigidly attached to the aero genetaror frame is fitted inside the inner rings of the radial bearings. Then the rotor shaft turns around the cylindrical beam thanks to the radial bearings. The yoke plates are rigidly attached to the rotor shaft. The tip cone is fitted with fasten bolts on the end of the shaft pointing against wind.

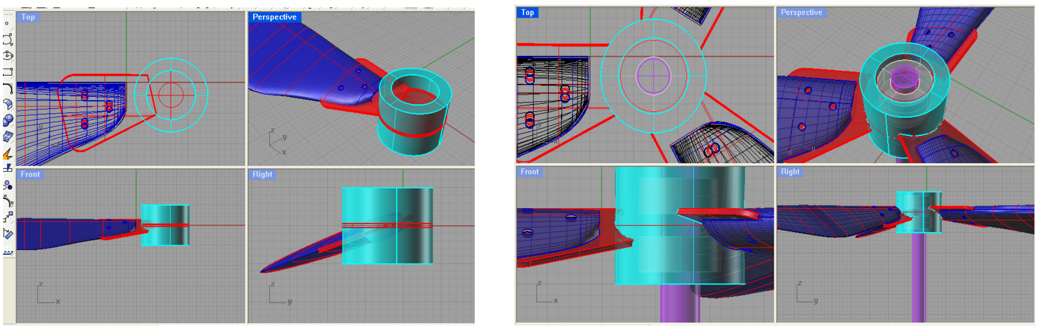
The tip cone protects the bearings inside the rotor shaft from the weather. The tip cone can also improve the turbine efficiency. According to Gamboa and Silvestre (2003), results from experiments show that adding a tip cone to a small or medium size wind turbine can increase it efficiency by something around 30%.

The tip cone was drawn having the same diameter of the rotor shaft and a height of 10.09 cm (fig. 9).



a) b)

Figure 7. a) Yoke plates. b) Blade angle of attack



a) b)

Figure 8. a) Rotor Shaft. b) Rotor with cylindrical beam, radial bearings, rotor shaft, blades and yoke plates

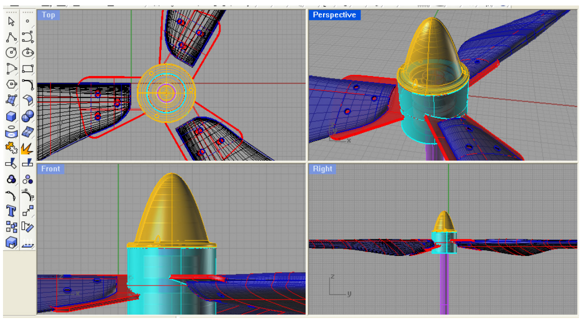


Figure 9. Complete rotor with tip cone

For the computational structural analysis, the finite element method was used on the software ABAQUS 6.8 (2008). The analysis was performed with one blade separately applying the load correspondent to the wind pressure.

The three dimensional blade models were loaded in the ABAQUS/CAE environment. The blade material was determined as being fiberglass.

The blade material properties were adopted as follows:

- Perfectly elastic over the full range of loading
- Properties for fiberglass with epoxy matrix: E_1 = 45 GPa; E_2=12 GPa; $G_{12} = G_{13} = G_{23}$ = 5.5 GPa; ν = 0,19
- Lamination sequence (15/45/90)

The blade model generated with the CAD software was only a surface, having no solid property. So, under the ABAQUS, environment, it was attributed a thickness of 1cm for the whole blade surface. The blade is a hollow piece.

The wind over the blade was considered constant and perpendicular to the blade plane of rotation. Then the wind load over one blade could be defined as a static and uniform pressure over the blade surface facing the wind. The dynamic pressure formula provides the wind load distributed over the blade:

$$P = (\rho v^2 /2)\sin \alpha \quad (1)$$

Being
P - the distributed pressure due to wind
ρ - the air density
v – the wind speed
α - the blade´s angle of attack.

The air density was taken at sea level, 0 °C : 1.29 kg/m³.
The maximum wind speed for rotor operation was defined as 5m/s and this was the value used in eq. (1).
The blade´s angle of attack is 70°.
The factor sinα works to compensate the lack of perpendicularity between the wind direction and the blade surface.
Replacing the above values on eq. (1):

$$P = (1.29*5^2/2)*0.939 = 15.14 \text{ N/m}^2$$

Figure 12 shows the wind load P applied over the blade.

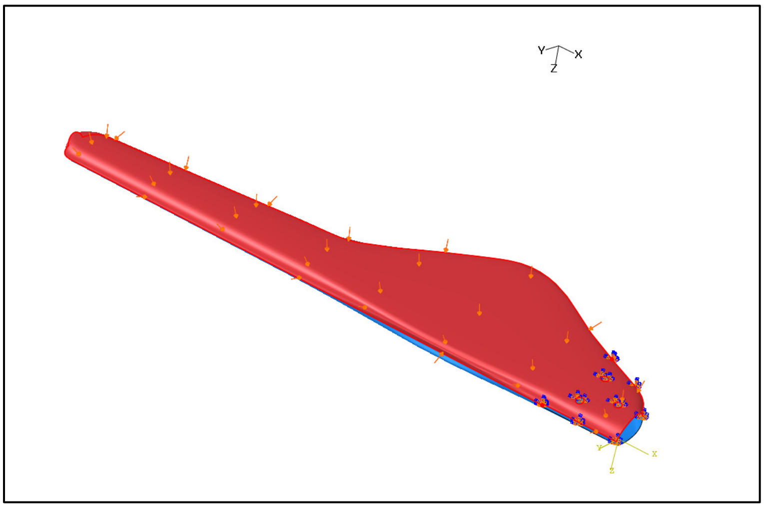


Figure 12. Wind dynamic pressure load

Each blades is considers rigidly attached to one yoke plate via the fasten bolts. So the blades are fully restrained on the circumference of the bolts holes, having no degree of freedom for translating or rotating along these circumferences.

The results (fig. 13 and 14) were analyzed in two ways: visual and numerically. The visual analysis consist in verifying the blade areas most stressed, intending to later reinforce these areas in an iterative exercise: starting again with the CAD software to change the drawing. The numerical analysis consists in verifying the piece structural limit and increases the loads until this limit is reached, when probably the piece presents a structural fail.

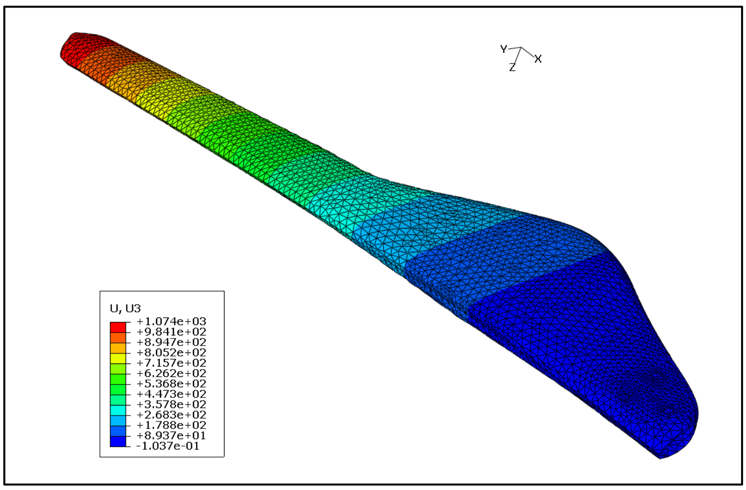


Figure 13. Results from the finite element analysis – displacements

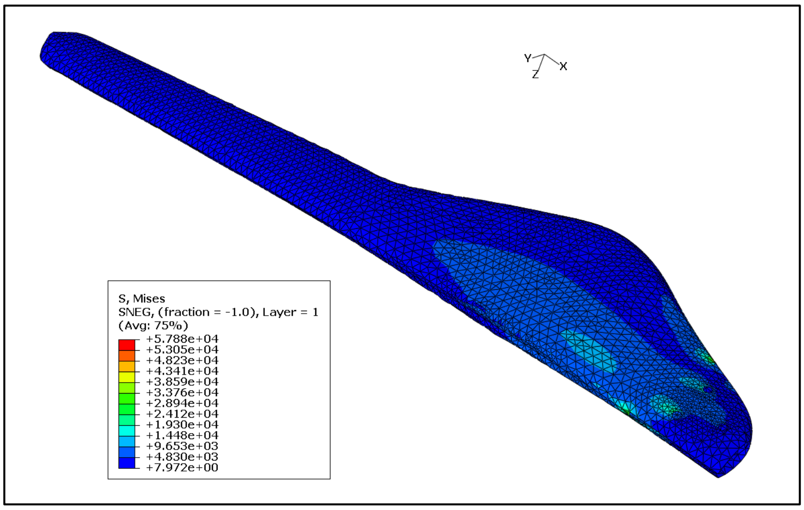


Figure 14. Results from the finite element analysis – von Mises stress for ply 1

As shown in figure 13, the regions around the holes of the blade are more stressed due to wind load. A simple analysis demonstrates the importance of to reinforce the areas where the stress levels are the higher.

Taking into account this evidence, it is possible to redrawn the model to improve its structural strength, keeping the intention of reaching an efficient project under the structural strength point of view.

6. FINAL CONSIDERATIONS

Analyzing the diversity of men activities, one can realize that the energy usage is present in almost all of them. Methods for energy extraction and conversion were created along the history. Some factors, as the mass production and the need to supply with electricity new machines created for the industrial revolution, contributed to a considerable growth in the consumption of electric energy.

In the scenario where the traditional energy sources tending exhaustion and with the growing aggression to the natural environment due to burning of fossil fuels, the alternatives sources of energy generation emerged expressively. Among them is the wind energy.

Recognizing the importance of the Earth biological preservation and the importance of the constant search for natural equilibrium, this work presented a brief history related to the energy in general and to the wind energy.

It was also presented a project with the function to describe, to model and to simulate part of the structure of wind energy generation equipment. The modeling as well the simulation presented evidences that applying the knowledge in virtual design with adequate tools favors the industrial design practices, propitiating a deep study for the product developing, mainly the aerogenerators, reveling possible emphasis on aerodynamic, on simplicity and cost reduction.

Virtual simulations performed cannot fully replace physical testing with prototypes, but have efficient results to determine the type of material to be used in the blades and the best design in order to ensure security and economy **.**

Thus, the article contributes to integration of the methodology applied here, the industry of small aero generators, aiming to make the equipment more efficient and cheaper.

Moreover, this study represents the beginning of a scientific research covering industrial design and engineering, in the area of renewable energies. The results presented are preliminary because the research is in progress.

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