AERODYNAMIC AND MODAL ANALYSES OF BLADES FOR SMALL WIND TURBINES

Jerson Rogério Pinheiro Vaz, jerson@ufpa.br
Dimitri Oliveira e Silva, dimitrioliveiras@hotmail.com
Alexandre Luiz Amarante Mesquita, alexmesq@ufpa.br
Erb Ferreira Lins, erb@ufpa.br
Federal University of Pará, Institute of Technology, Faculty of Mechanical Engineering, Belém-Pará, Brazil

João Tavares Pinho, jtpinho@ufpa.br
Federal University of Pará, Institute of Technology, Faculty of Electrical Engineering, Belém-Pará, Brazil

Abstract. *During the last decades the demand for renewable electric energy production has led to an increasing in research on wind energy technology. This technology involves technical disciplines such as aerodynamics, structural dynamics, mechanical as well as electrical engineering. As the improvements in these areas it will lead to further cost reductions, and for the medium term, wind energy will be able to compete with conventional fossil fuel power generation technology. The usage of this type of energy generation is quite adequate in certain regions of Amazon, where there is difficulty of the arrival of electric transmission lines. This paper has as primary objective to present the results obtained in the studies done in 41 airfoil shapes more used commercially for construction of blades for small wind turbines. According to operation conditions and dimensions of a rotor, an aerodynamic analysis was performed and chosen the profile that presents the best power coefficient and angle of attack. In the second part of this paper, a dynamic analysis was made. Through the finite element method, a modal analysis was accomplished and the first four modes of vibration of the blade chosen in the previous analysis were determined.*

Keywords*: Aeolian energy, wind turbine, airfoil shapes, mode shapes, modal analysis.*

1. INTRODUCTION

The use of wind turbines to generate electricity has advantages as: generation without pollution, no environmental impacts, fast installation and commissioning capability, low operation and maintenance cost and taking advantage of using free and renewable energy (Shokrieh and Rafiee, 2006). In remote areas, wind energy can be used for charging batteries or can be combined with a diesel engine to save fuel whenever wind is available. Some of the drawbacks are: the noise produced from wind turbine operation and the fact that wind energy can only be produced when nature supplies sufficient wind (Hansen, 2008).

Wind turbine transforms the kinetic energy in the wind to mechanical energy in a rotor and shaft and finally into electric energy in a generator. In general, wind turbine systems consist of five physical components: rotor, transmission, generator, support structure, and control system (Tempel and Molenaar, 2002). The blade of the rotor is the most important component in a wind turbine which nowadays is designed according to a refined aerodynamic science in order to capture the maximum energy from the wind flow (Shokrieh and Rafiee, 2006). The efficiency of a rotor is characterized by its profile (airfoil section) and the corresponding aerodynamic design. In aerodynamic design, extensive calculations will be necessary in order to determine the blade parameters, such as chord, thickness and twist distributions and taper, which are matched with the selected airfoil section (Habali and Saleh, 2000).

Nowadays, blades of horizontal-axis wind turbine (HAWT) are completely made of composite materials. Composite materials satisfy complex design constraints such as lower weight and proper stiffness, while providing good resistance to the static and fatigue loading (Shokrieh and Rafiee, 2006). Thus, besides the aerodynamic design, attention must be paid to dynamic analysis in order to increase their reliability. The fatigue estimation of a rotating blade can be useful for preventing blade breakage, which is a very frequent problem in the use of wind turbine. The estimation of fatigue for a rotating blade must go through several steps of calculation: among them the calculation of mode shapes and frequencies and the computation of displacements and stresses acting on the blades (Mahri and Rouabah, 2002). The numerical computation of the natural modes of vibration of the blade is necessary to prevent the resonance condition in a design stage and to comparison with experimental results in order to validate the numerical model.

This paper focuses some aspects in a theory of blade design. The work is divided into two parts. The first one describes a methodology to choose the profile that best fits the wind conditions for a wind turbine that will be built in the Amazon region. According to operation conditions and dimensions of the rotor, an aerodynamic analysis was performed and chosen the profile that presents the best power coefficient and angle of attack. In this study 41 profiles were analyzed. In the second part of this work, a numerical modal analysis is performed using the finite element method. In this analysis were determined the first four modes of vibration of the blade chosen in the previous analysis.

2. DETERMINATION OF THE ROTOR AIRFOIL

The procedure for the specification of blade profile results from the determination of the optimal angle of attack and the maximum power coefficient of some profiles suitable for the design of rotors of small wind turbines. For the study, it was used the Blade Element Moment method (BEM) considering the correction of Glauert (1935) and Prandt (Eggleston and Stoddard, 1987). The empirical model of Glauert corrects the axial induction factor when it reaches values greater than 0.4, since the method fails for these values. The factor Prandt considers a finite number of blades. Table 1 shows the profiles studied in this work.

Table 1. Profiles used for the aerodynamic design of the blade.

Aerodynamics Profiles		
E387	NACA23012	NACA64-221
S822	NACA63-209	NACA64$_4$-421
SD2030	NACA63-412	NACA65-415
FX63-137	NACA63-415	NACA65$_2$-415
S834	NACA63-615	NACA65-418
SH3055	NACA63-218	NACA65$_3$-418
NACA1412	NACA63-418	NACA65-618
NACA2408	NACA63-618	NACA65$_3$-618
NACA2410	NACA63-221	NACA65-221
NACA2412	NACA63-421	NACA65-421
NACA2415	NACA64-412	NACA65$_4$-421
NACA4412	NACA64-415	NACA747A315
NACA4415	NACA64-418	NACA747A415
NACA4418	NACA64-618	

The Blade Element Moment method was implemented in MATLAB language and the computational simulations were made for the following operational characteristics and dimensions of the rotor:

- Length of the blade: 1,75 m;
- Hub radius: 0,15m;
- Wind average speed: 3 m/s;
- Rotational speed: 130 rpm

The results obtained for the more efficient profiles are listed in Table2.

Table 2. Profiles more efficient for wind with average speed of 3 m/s.

Aerodynamic Profiles	Maximum Power Coefficient	Angle of Attack (^{o})
NACA64$_4$-421	0.4660	6.5918
NACA65$_3$-418	0.4610	4.3469
NACA65$_4$-421	0.4660	18.4285

The NACA65$_4$-421 has a maximum power coefficient (C_p) for an angle of attack of 18,4285^o, where the stall is almost to occur (see Fig.1), causing a reduction in the lift coefficient generated by an airfoil as angle of attack increases. This situation does not occur with the NACA64$_4$-421. The plot of the Fig. 2 shows that for an angle of attack of 4,3469^o (corresponding to the maximum C_p) the lift coefficient is quite far from the beginning of stall, resulting in the possibility of the rotor experience higher angles of attack. Thus, the NACA64$_4$-421 is the profile chosen for the turbine blade to be manufactured. Figure 3 shows an illustration of this blade.

For the NACA64$_4$-421, the C_p remains almost constant for angles of attack between 3^o and 6^o and the maximum C_p (46,6%) occurs for an angle around 6,6^o (Fig. 4), however, for higher angles of attack the C_p decreases abruptly.

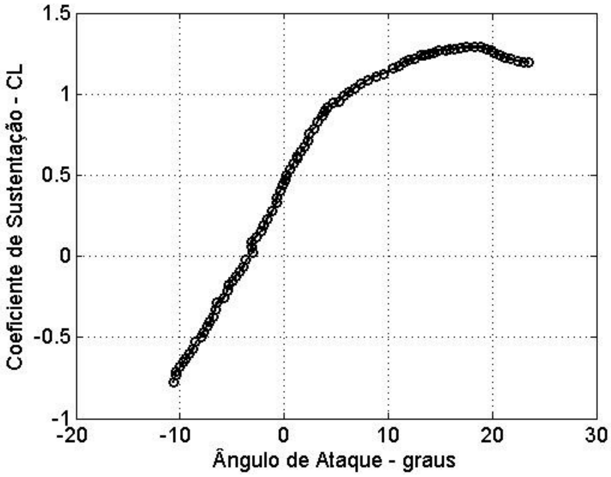

Figure 1. Lift coefficient in relation to the angle of attack for the profile NACA 64_4-421.

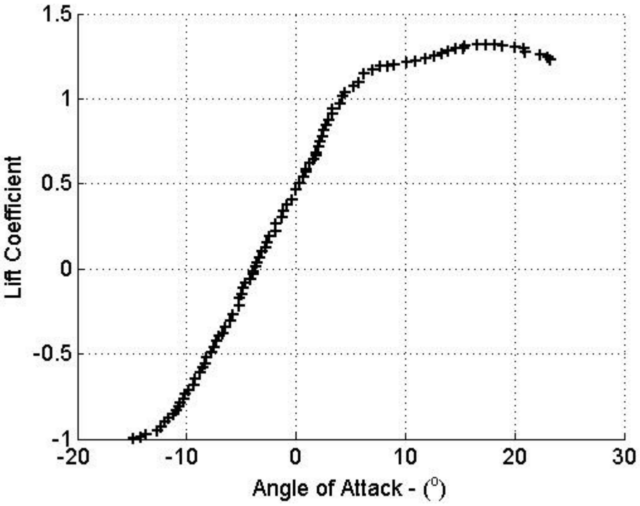

Figure 2. Lift coefficient in relation to the angle of attack for the profile NACA 64_4-421.

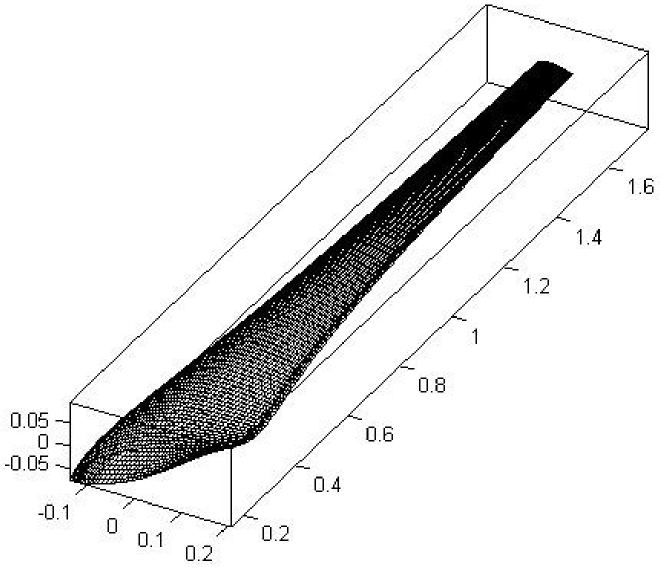

Figure 3. 3D blade with the airfoil NACA 64_4-421.

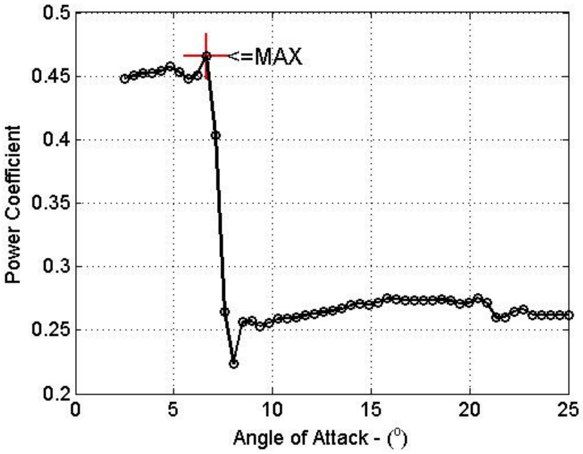

Figure 4. Power coefficient as function of the angle of attack for the profile NACA 64_4-421.

In fact, the use of angles of attack calculated for a maximum efficiency does not always correspond to the best rotor system. It is necessary to examine the continuity of the curve established for the power coefficient. The immediate response (if the angle of attack used is appropriate) is the plot of the power coefficient as a function of wind speeds and also as a function of tip speed ratio (TSR). When abrupt decays occurs in the curves of C_p, as observed in Figs. 5 and 6 for angle of attack 6^o, it means that, probably the designed rotor when experiences higher wind speeds it will lose lift force. Therefore the Fig. 5 and Fig. 6 show that the angle of 4^o is actually the best.

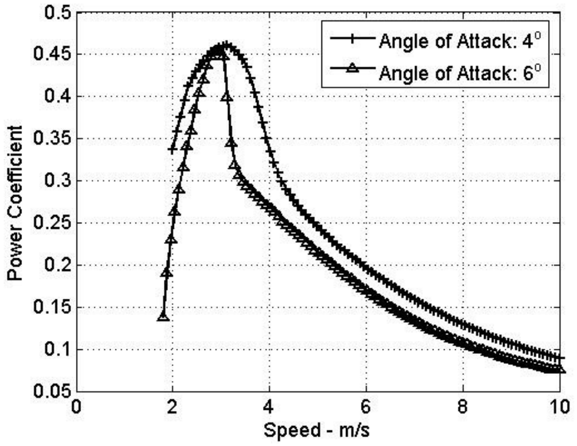

Figure 5. Comparison between curves of C_p as a function of wind speed for different angles of attack.

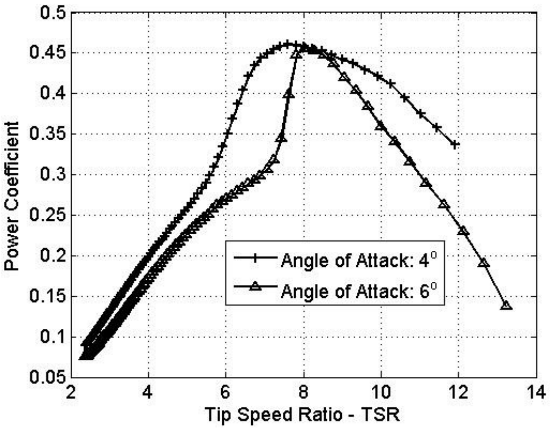

Figure 6. Comparison between curves of curves of C_p as a function of the TSR for different angles of attack (NACA 64_4-421).

Figs. 7 and 8 show the chord distribution and the pitch angle as a function of the rotor radius.

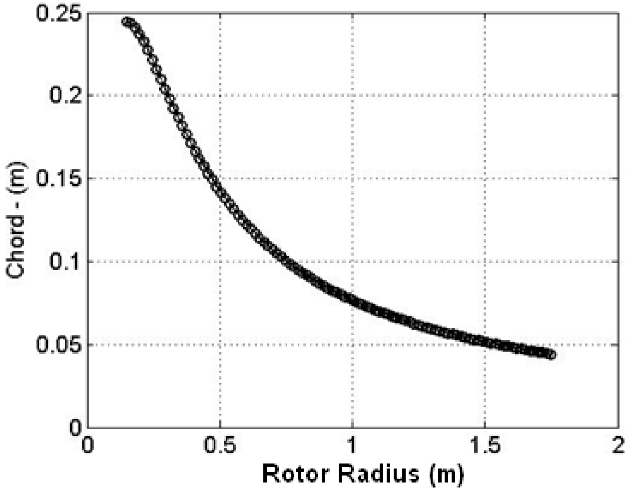

Figure 7. Chord distribution for wind rotor using the airfoil NACA 64_4-421.

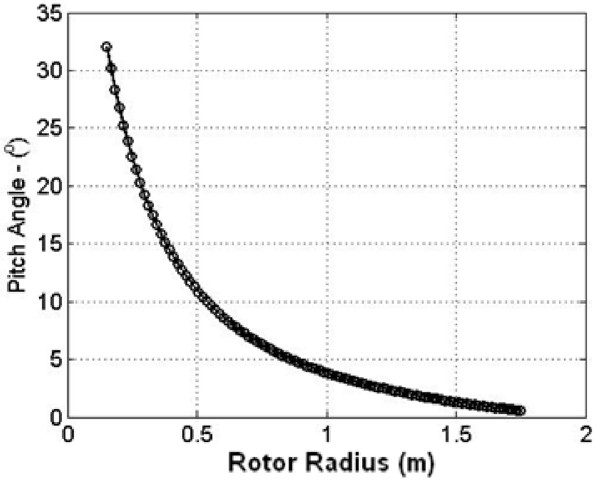

Figure 8. Pitch angle distribution for wind rotor using the airfoil NACA 64_4-421.

3. STRUCTURAL DYNAMIC ANALYSIS

A structural dynamic analysis means to predict the loads on a wind turbine throughout its lifetime and hence the stress in the material can be computed. Once the dynamic stresses are known, it is possible to calculate the fatigue damage using standard methods such as Palmgren-Miner rule (Hansen, 2008). Fatigue is a very important issue in a wind turbine design. Several factors expose wind turbine blades to the fatigue phenomena (Shokrieh and Rafiee, 2006):

- Long and flexible structures;
- Vibration in its resonant mode;
- Randomness in the load spectra due to the nature of the wind;
- Continuous operation under different conditions;
- Low maintenance during lifetime.

For design against fatigue, loads must be determined. All of the loads that occur can be categorized as follow (Shokrieh and Rafiee, 2006):

- Aerodynamic loads on the blade;
- Weight of the blade;
- Annual gust;
- Changes in the wind direction;
- Centrifugal force;
- Force that arise from start/stop angular acceleration;
- Gyroscopic forces due yaw movements;
- Activation of mechanical brake;
- Thermal effect.

A necessary tool for accomplish a structural dynamic analysis is a computer simulation of the dynamic system, with which to study and understand its dynamic behavior and determine how the system should be modified to change that behavior in favorable directions. Adequate models can and must permit designers to study and improve the system behavior as though they were running the real turbine (Spera, 1994). For these computer simulations the finite element method (FEM) is currently widely used. This methodology permits that accurate models of the blade and the whole system can be obtained.

In order to have an accurate computational model it is necessary validate this model with experimental data. It is generally accomplished using modal data, i.e., the mode shape and natural frequencies of the numerical (FEM) model are computed and validate by mode shape and natural frequencies from experimental modal analysis.

3.1. Numerical Modal Analysis

Analytical (or numerical) and experimental procedures for determining mode shapes and frequencies are referred to as modal analysis. Mode shapes and natural frequencies are determined primarily by the distribution of mass and stiffness throughout the structure and by its boundary conditions. Rotation can alter the natural frequencies of certain mode shapes, when centrifugal and Coriolis forces change stiffness (Spera, 1994). A plot that shows the variation of the natural frequencies as a function of the rotational speed is the Campbell diagram. Figure 8 shows the results of a Campbell diagram displaying the results of a modal analysis in an HAWT (Yamane *et al*., 1992). In this plot the thick solid lines and dotted lines denote natural frequencies, and the radial lines of *nP* can be regarded as the frequency of the excitation force (*P* means the rotational speed and *n* is a integer multiple of the rotational speed). The resonance is a phenomenon which occurs in structure when the frequency of the excitation equals or nearly equals one of the modal frequencies of the structure. Thus, in Fig. 9, every intersection of a radial line (*nP*) and a modal frequency line is a potential resonance. However, in order to validate models is more common accomplish the numerical and experimental modal analysis for the structure without rotation. Therefore, the numerical modal analysis for the blade of this work does not take into account the rotational speed of the rotor. This analysis is shown in the next section.

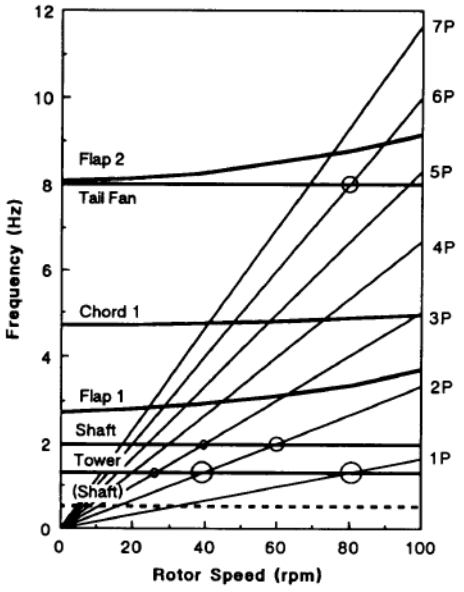

Figure 9. Campbell diagram of a wind turbine (Yamane *et al*., 1992).

3.2. Results of Modes Shapes and Frequencies of the Blade with Profile NACA 64_4-421

Once defined the blade profile for the wind turbine that will be built in a site in Amazon, the next step is to create the finite element model of the blade to obtain the modal parameters (mode shapes and natural frequencies). As the rotor is very short, the blade will be manufactured in a peculiar manner: first is created a mold of the blade according to its length and profile. After that, this mold is filled with polyurethane, and hence, it is inserted an aluminum tube inside of the mold. This tube will make the blade stronger and stiffer and will also have the function of connecting the blade to the hub. After drying the mixture, the polyurethane and the tube are taken off of the mold; hence a thin layer of glass fiber is placed externally to the polyurethane in order to give more strength to the blade.

For the analysis in ANSYS, the material properties of the blade are listed in Table 3. The geometric data of the blade are shown in Table 4. The tube of aluminum has 0.020 m of external diameter and 0.016 of internal diameter.

Table 3 – Material properties of the blade.

Material	Aluminium	Polyurethane	Glass fiber
Density	2700 kg/m³	1150 kg/m³	2440 kg/m³
Modulus of elasticity	70 GPa	1.72 MPa	68.9 GPa
Coefficient of Poisson	0.35	0.103	0.183

Table 4 – Dimensions of the blade.

Profile	NACA 644-421
Length of the blade	1.75 m
Maximum chord	0.26 m
Minimum chord	0.05 m

The characteristics of the pre-processing in the analysis are:

- Finite element: Solid 45;
- Mesh: 268459 elements;
- Mode shape extractor method: Block Lanczos;
- Boundary conditions: Fixed-free. The aluminum tube is fixed to the hub.

The natural frequencies computed are listed in Table 5. The blade mesh is shown in Fig. 10 and the mode shapes are shown in Fig. 11 to 14. A mode shape is called “flapwise” when it is predominantly vertical (displacements in direction *Y* in the Figures), “edgewise” refers to horizontal motion (displacements in direction *X*) and “pitchwise” or “torsion” to cord rotation.

Table 5 – Natural frequencies.

	1st Mode (flapwise)	2nd Mode (edgewise)	3rd Mode (flapwise)	4th Mode (flap-torsion)
Frequency [Hz]	15.08	16.24	48.03	125.99

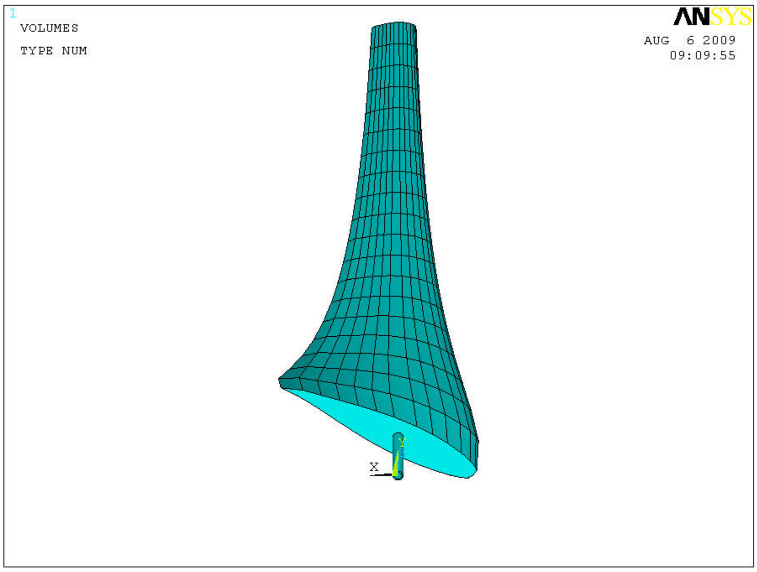

Figure 10. Blade FEM mesh.

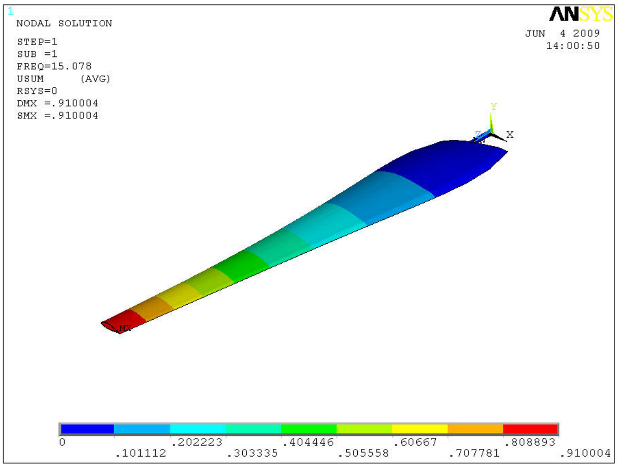

Figure 11. First mode shape of the blade (flapwise mode).

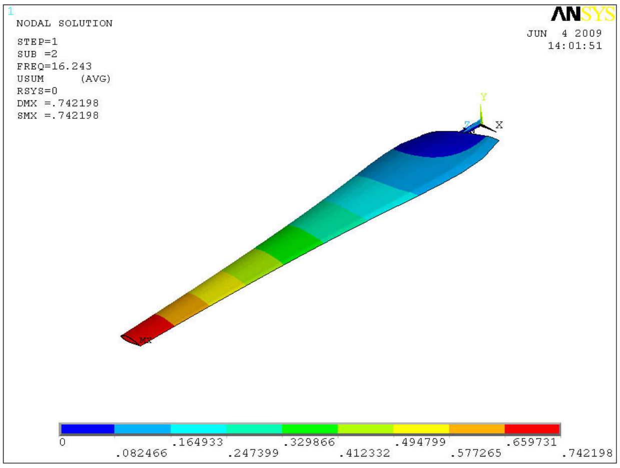

Figure 12. Second mode shape (first edgewise mode).

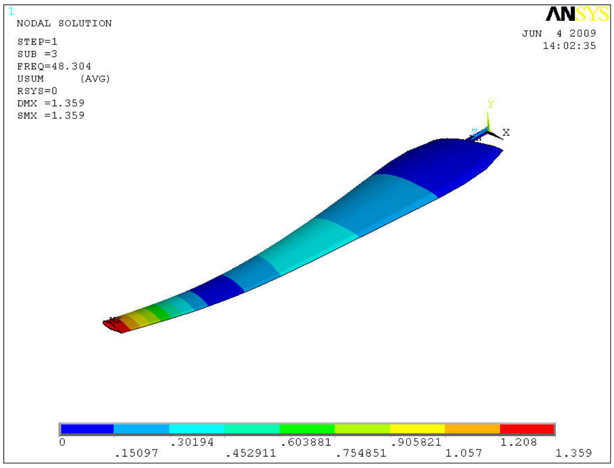

Figure 13. Third mode shape (flapwise mode).

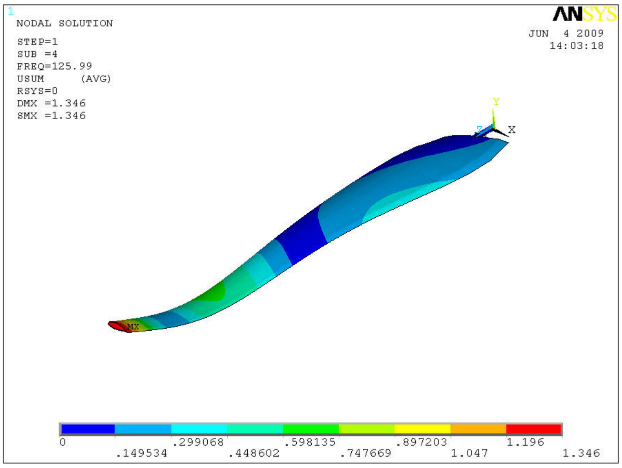

Figure 14. Forth mode shape (flap-torsion mode).

4. CONCLUDING REMARKS

This paper presented an aerodynamic and a dynamic analysis of a blade for a wind turbine. This turbine will be constructed in a localization in Amazon Region where does not exist connection to the national grid of electric energy. In aerodynamic analysis, it was determined a profile that results in better power coefficient and angle of attack.

In the numerical modal analysis, through finite element method, the four first natural modes of vibration were calculated. It was observed that the first modal frequency (904.8 rpm) is higher than the nominal rotational speed of the turbine (130 rpm), thus avoiding resonance.

5. ACKNOWLEDGMENTS

The authors would like to thank the CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for the financial support of this project.

6. REFERENCES

Eggleston, D. M., Stoddard, F. S., 1987, "Wind Turbine Enginering Design", Van Nostrand Reinhold Company, New York.

Glauert, H., 1935, "AirPlane Propellers, in Aerodynamic Theory", Spring Verlag, ed. W. F. Durand, pp. 169-360.

Habali, S. M., Saleh, I. A., 2000, "Local design, testing and manufacturing of small mixed airfoil wind turbine blades of glass fiber reinforced plastics. Part I: Design of the blade and root", Energy Conversion & Management, 41, pp 249-280

Hansen, M., 2008, "Aerodynamics of Wind Turbines", 2nd Edition, Earthscan.

Mahri, Z. L., Roubah, M.S., 2002, "Fatigue Estimation for a Rotating Blade of a Wind Turbine". Rev. Energ. Ren., Vol.5, pp39-47

Shokrieh, M. M., Rafiee, R., 2006, "Simulation of fatigue failure in a full composite wind turbine blade", Composite Structures, 74, pp 332–342

Spera, D. , 1994, "Wind Turbine Technology", ASME Press.

Tempel, J.V., Molenaar, D.P., 2002,"Wind Turbine Structural Dynamics –A Review of the Principles for Modern Power Generation, Onshore and Offshore", Wind Engineering, Vol 26, NO. 4 , pp 211–220

Yamane, T., Matsumiya, H., Kawamura, S., Mizutani, H., Nii, Y, Gotanda, T., 1992,"Vibration Characteristics of an Experimental Wind Turbine with a 15 m Teetered Rotor", The Japan Society of Mechanical Engineers, Vol. 35, No 02, pp. 268-273

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.