23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

WIND TURBINE SIMULATION FOR LOADING CALCULATIONS USING AEROELASTIC MODELLING

Aigbokhan Isaiah Asibor
Federal University of Pernambuco, Av. Prof. Moraes Rego, 1235, Recife-PE, Brazil
issy_asibor@yahoo.com
Jairo Rodríguez García
Polytechnic School of Engineering of Gijon, Multi-Purpose Building, Module 1 - Ground Floor. 33203, Gijón
jairomrg@gmail.com
Mario Castañeda Ramos
Polytechnic School of Engineering of Gijon, Multi-Purpose Building, Module 1 - Ground Floor. 33203, Gijón
cmario00@gmail.com
Ezequiel Costa Malateaux da Silva
Petrobras Research Center (CENPES) - Gas, Power and Gas to Chemicals R&D Department, Av. Horácio Macedo, 950, Rio de Janeiro-RJ, Brazil
ezequiel.malateaux@petrobras.com.br
Alex Maurício Araújo
Federal University of Pernambuco, Av. Prof. Moraes Rego, 1235, Recife-PE, Brazil
ama@ufpe.br

Abstract. *Currently, the design and development of MWs wind turbines are based mainly on results from computational simulations using aeroelastic codes. The wind turbine dynamics can be analyzed through experimental measurements or simulations using numerical computational codes. The aim of this work is to perform a preliminary turbine analysis using a comparative procedure between the steady calculation results as a function of wind speed and the response obtained from dynamic simulations. To carry out these simulations, a numerical model of a wind turbine present in the aeroelastic code was used and 9 degrees of freedom were analyzed based on the proposed procedure for estimating the performance, the structural loads and the dynamic responses (3 degrees of freedom for the blades, 2 for the drive train, 3 for the nacelle and 1 for the tower).*

Keywords: *wind turbine design, aeroelastic code, dynamic simulation*

1. INTRODUCTION

The studies and analysis of wind turbine dynamics currently constitute an important discipline that belongs to the field of knowledge of Wind Energy Conversion Systems (WECS).

The aerodynamics of wind turbines is nonlinear, unsteady and complex since they are forced by stochastic wind disturbances and a number of rapidly changing loads that can cause fatigue damage and reduce the life of the turbine (Wilson *et al.*, 2009).

A dominant and consistent trend in commercial wind turbine production throughout the years has been growth in the size of the rotor and lowered cost-of-energy in order to compete with conventional systems (Hansen, 2014). However, the choice of rotor and generator size depends heavily on the wind speed distribution and the wind energy potential at a prospective location (G.L., 2010). Large turbine sizes will give rise to loads that vary along the blade and change quickly due to wind gusts and other varying wind conditions.

As a result, numerical modelling of wind turbines through more efficient and robust dedicated load calculation tools has become more and more important for predicting the load levels and variations on all components.

Accurate models must contain many degrees of freedom (DOFs) to capture the most important dynamic effects. The rotation of the turbine adds complexity to the dynamic modeling. However, in order to perform structural analysis for evaluating design trade-offs, realistic structural models are needed even though technical data from manufacturers is very limited.

The design tool 'Bladed' meets these criteria and also helps the user in many other parts of the design or research process (Garrad Hassan and Partners, 2012). The tool contains the capability of steady calculations for preliminary turbine analysis and dynamic simulations that can be used for design load calculations. The steady calculations allow the user to analyze the performance of the turbine as a function of wind speed, azimuth, pitch and yaw in different conditions (Urbano *et al.*, 2014). The shape and design of wind turbine blades and towers have a huge influence on the turbine's performance and power output and can vary significantly from one turbine to the other (Wilson *et al.*, 2009).

A 2 MW variable speed variable pitch (VSVP) wind turbine model available in the GL Bladed Educational Version licensed to the Federal University of Pernambuco is used for this study. The turbine model contains distributed properties for the tower and blades and includes models for the nacelle and drive train dynamics.

The operating regions of a variable speed wind turbine and the chosen degrees of freedom will be explained next.

1.1 Operating Regions of a Variable Speed Wind Turbine

Figure 1 shows the operating regions of a variable speed variable pitch wind turbine (VSVP). In region I, the wind speed is below the cut-in speed, so the wind turbine does not operate in this region. Region II is an operational mode in which it is desirable to capture as much power as possible from the wind since the wind speed lies below the rated value in this region. Region III represents the transition of the control systems. The operation in region IV occurs above rated wind speed. In this region, the turbine must limit the fraction of the wind power captured so as not to exceed electrical and mechanical design loads. The generator torque is kept constant and the pitch angle is varied through the pitch control strategy (Wu *et al.*, 2011).

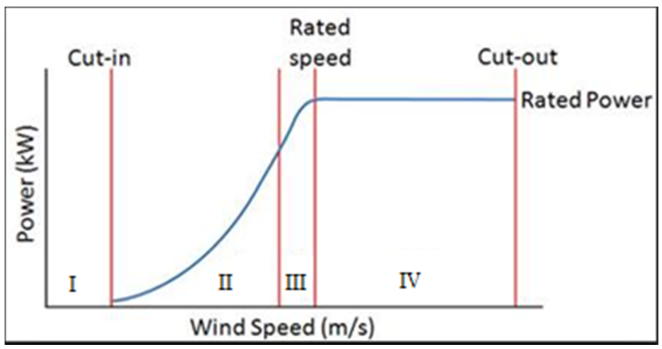

Figure 1. Operating regions of a variable speed variable pitch wind turbine (adapted from the authors)

1.2 Degrees of Freedom and Deflections

In order to estimate the aeroelastic behavior of a wind turbine, it is necessary to perform representative simulations of various loading scenarios to assess the structural dynamic behavior of the blades, inertia of the rotating components in the nacelle, structural dynamics of the tower and the control system behavior. Figure 2 shows the rotor blade coordinates system employed by GL Bladed.

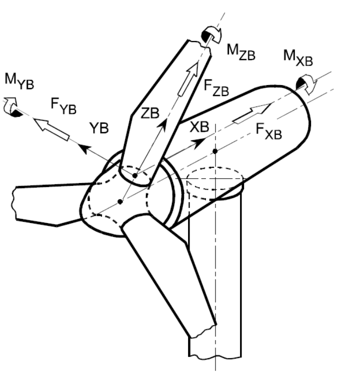

Figure 2. Coordinate system and degrees of freedom of the wind turbine blade root (G.L., 2010)

Table 1 depicts the main loads acting on the tower, on the blades and on the rotor hub according to GL Bladed.

Table 1. Main loads acting on the tower, blades and rotor hub.

	Load	Dimension	Description
Blade root	M_x bending moment	N.m	Blade deflection perpendicular to the local chord (blade edge)
	M_y bending moment	N.m	Blade deflection parallel to the rotor plane (blade flap)
Hub center	M_x torque	N.m	Total rotor mechanical torque
	M_y moment	N.m	Tilting moment
	M_z moment	N.m	Yaw moment
	F_x force	N	Thrust force
Tower base	M_x bending moment	N.m	Tower deflection in the rotor plane (tower side-to-side)
	M_y bending moment	N.m	Tower deflection out of the rotor plane (tower fore-aft)

2. SIMULATIONS AND ANALYSIS

First, the steady calculations will be explained. Then, the dynamic simulations will be discussed.

2.1 Steady Calculations

The steady state analysis of the nacelle degrees of freedom, drive train torque analysis, degrees of freedom of the blades and tower will be discussed in this section.

2.1.1 Nacelle degrees of freedom

Figure 3 illustrates the behavior of the nacelle in terms of translational degrees of freedom as a function of wind speed ranging from 4 m/s to 25 m/s, which represents the cut-in and cut-out reference wind speed of the studied wind turbine.

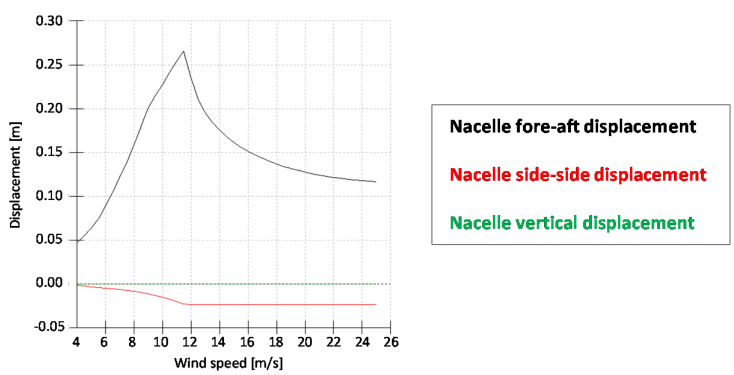

Figure 3. Frontal, lateral and vertical displacements of the nacelle

The nacelle fore-aft displacement occurs along the x axis of the nacelle reference system shown in Fig. 2. According to Fig. 3, the nacelle displacement increases towards the positive x-axis as from 4 m/s reaching its maximum displacement at 12 m/s (the rated wind speed), at which the pitch control begins to act. For wind speeds greater than 12 m/s, the displacement decreases significantly until 15 m/s. For wind speeds higher than 15 m/s, the displacement tends to stabilize at around 11 cm until the cut-out speed is reached.

When the wind turbine is operating in region IV (shown in Fig. 1), if the wind speed decreases, the nacelle fore-aft displacement begins to increase, reaching its maximum slightly before the rated wind speed. For lower wind speeds, the pitch control stops working and the wind turbine returns to the operational mode region where it is desirable to capture as much power as possible from the wind. In this region, the nacelle displacement falls approximately linearly as the wind speed decreases until the cut-in value.

For the nacelle side-to-side displacement, which occurs along the y-axis, it can also be observed that the nacelle displacement increases from 4 m/s and reaches its maximum displacement at 12 m/s. For wind speeds greater than 12 m/s, the nacelle maintains the same displacement value until the cut-out speed.

When the wind turbine is operating in region IV, if the wind speed decreases, no variation is observed in the nacelle side-to-side displacement until region II. As the wind speed continues to decrease, the nacelle displacement decreases (in absolute terms) until the cut-in value is attained.

The nacelle side-to-side displacement has a negative sign due to the blade shapes and how it is coupled to the rotating hub. This causes a clockwise rotation which thus induces the displacement of the nacelle in this sense.

In absolute comparison terms, it is found that the magnitude of the nacelle side-to-side amplitude displacement is approximately 10% of the nacelle fore-aft amplitude displacement.

The degree of freedom corresponding to the vertical linear displacements of the nacelle has null values. This result indicates that there are not enough vertical forces acting on the nacelle to provoke vertical displacement during the turbine operation regime.

2.1.2 Low speed shaft and high speed shaft torque analysis

The torques produced in the low (T_{LSS}) and in the high speed (T_{HSS}) shafts increase approximately linearly until a wind speed of about 9 m/s. From this wind speed, the torques continue to rise at an even higher rate until 12 m/s. For higher wind speeds, the pitch control acts keeping the torque values constant. The shape of the high-speed shaft torque graph (HSS) is similar to the low-speed shaft one (LSS), as shown in Fig. 4, given that they are related by the gear ratio of the gear box.

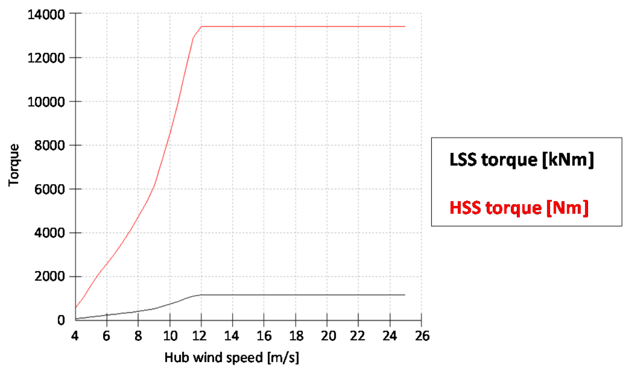

Figure 4. Low (LSS) and high (HSS) speed shaft torques

The lower torque in the high speed shaft is compensated by its higher speed, considering the losses in the gearbox.

At low wind speeds, the rotor speed increases as wind speed increases. This happens in order to keep the tip speed ratio constant at the value that maximizes the power coefficient. For wind speed values around 9 m/s, the maximum rotor speed is reached. From 9 m/s to 12 m/s, the generator torque demand increases, as shown in Fig. 5. This ensures that the power will keep rising even without an increase in rotor speed. The maximum generator torque is reached at a wind speed approaching 12 m/s. For this wind speed value, the turbine is at full power since the generator torque and the rotor speed are at their maximum values. Beyond 12 m/s, it is necessary to pitch the blades progressively towards feather in order to keep the power output constant, reducing the power coefficient and avoiding excessive turbine loading by reducing the thrust forces acting on the turbine.

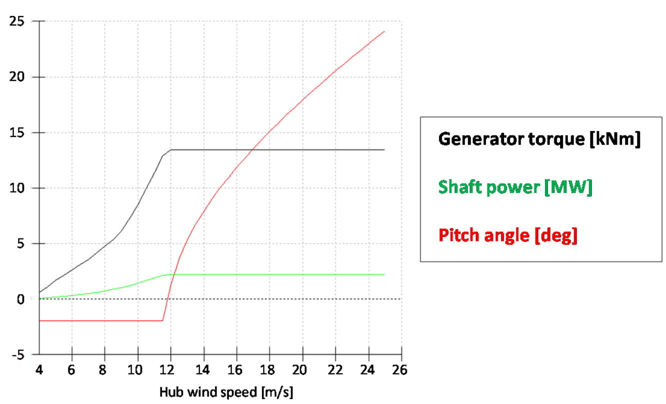

Figure 5. Variation of the generator torque, pitch angle and generated electric power

2.1.3 Blades and tower degrees of freedom

The blade root M_x and M_y bending moments, the M_z torsional moment, the tower M_y bending moment and the pitch angle are all represented in Fig. 6, 7 and 8. The M_{xy} value is the magnitude of the total bending moment at a given position on the blade.

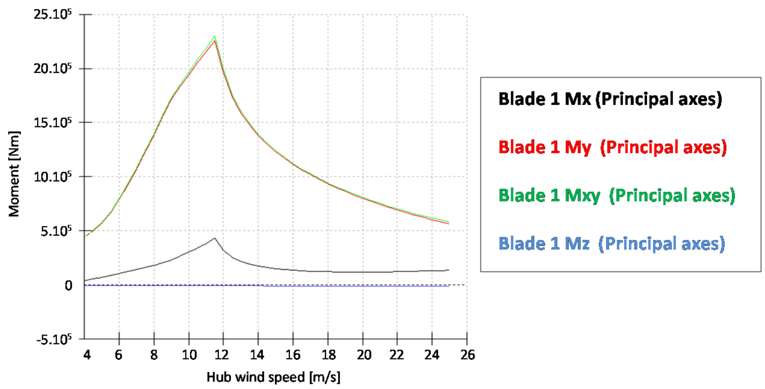

Figure 6. Blade root bending and torsional moments

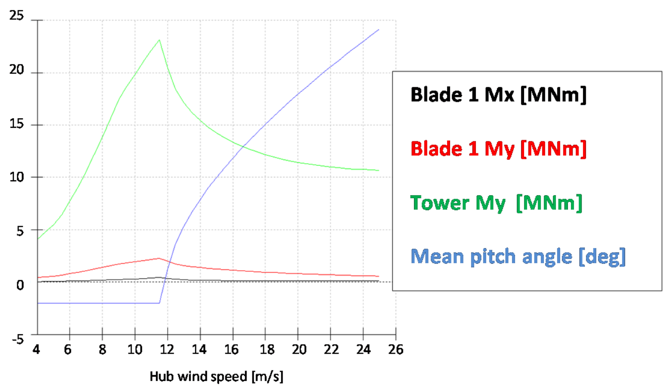

Figure 7. Blade root and tower bending moments and pitch angle

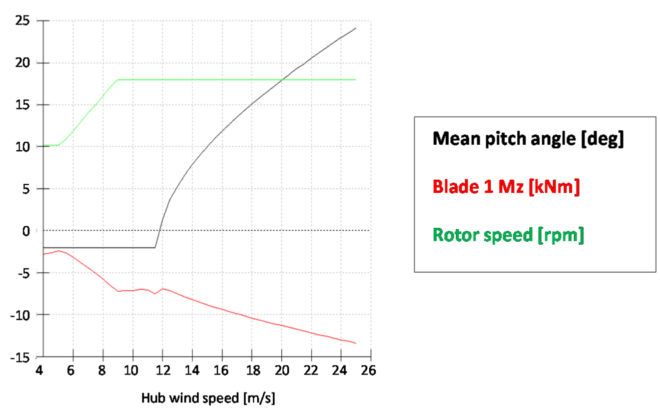

Figure 8. Mean pitch angle, blade torsional moment and rotor speed

From Figs. 6 and 7, the blade and tower loads show a similar profile with loading increasing up to the rated wind speed (from 4 to 12 m/s) and then falling at higher wind speeds. This is typical for many key structural loads since it shows that when the turbine is operating, the tower and blades experience their highest loading around rated wind speed. At higher wind speeds, the pitching of the blades reduces the loads.

The M_x tower load and the blade root loads have also the same behavior. From 5 m/s to 9 m/s, the blade torsional moment (M_z) increases as the rotor speed increases, as shown in Fig. 8. For wind speeds above 9 m/s, the rotor speed remains constant even though the wind speed increases, resulting in is constant torsional moment at the blades.

Beyond 12 m/s, the M_z moment increases (in absolute values) due to the pitch control action.

The turbine shuts down at the cut-out wind speed, protecting the wind turbine from consequences of unexpected faults.

Moreover it should be observed that for all steady calculations, features such as turbulence, wind shear and structural resilience are all ignored including the dynamic details of the turbine control system. In reality, these effects can also lead to high turbine loading across the full range of wind speeds.

2.2 Dynamic Simulation Analysis

The purpose of carrying out the dynamic simulation analysis of the wind turbine is to describe more realistic operating conditions in comparison to the steady state regime for the considered degrees of freedom. The dynamic simulations will be performed with the 60 second time series baseline educational version of GL Bladed® shown in Fig. 9.

In the indicated range, there is a sequence of three gusts where the maximum wind acceleration as represented in Fig. 9 occurs from 30 s (10.5 m/s) to 40 s (17.5 m/s). A maximum deceleration is observed from 17.5 m/s at 40 s to 10 m/s at 50 s, which almost characterizes a symmetrical gust. This comparative study will be conducted between 30 s and 50 s.

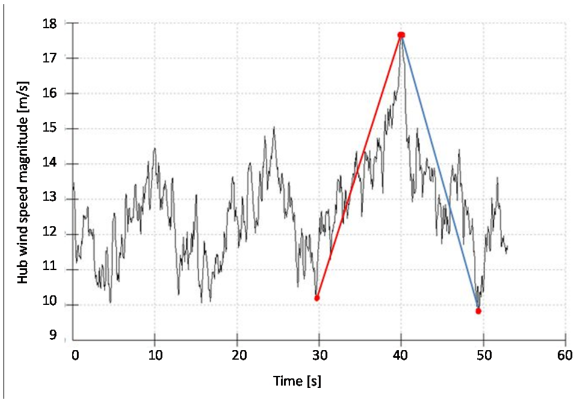

Figure 9. A 60 s time series used for the dynamic simulations where the maximum gust is emphasized from 30 to 50 s.

2.2.1 Analysis of the nacelle degrees of freedom

In the steady state regime, the nacelle fore-aft displacement increases until the rated speed, decreasing for higher wind speeds (Fig. 3). In Fig. 10a, the same dynamic behavior is observed for this displacement. Considering the steady state regime, the nacelle side-side displacement increases (in absolute values) until the rated wind speed, maintaining a constant value for higher wind speeds. In the dynamic case, Fig. 10b shows that for wind speeds higher than 12 m/s this displacement does not remain constant. However, a vibration process occurs with a constant period (T) of about 2 seconds, regardless of the wind speed. Since the maximum nacelle fore-aft displacement is around the same amount for both regimes (0.025 m), it can be said that the wind speed only affects the amplitude of the vibration which occurs in the transient regime.

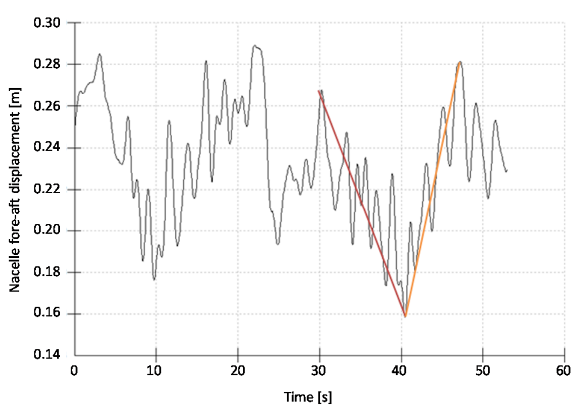

Figure 10 (a). Nacelle fore-aft displacement.

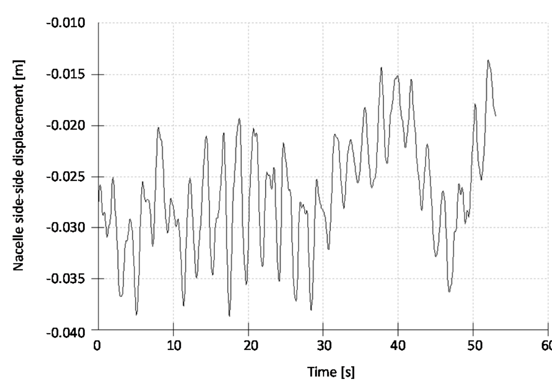

Figure 10 (b). Nacelle side-to-side displacement.

2.2.2 Low Speed and High Speed Shaft Torque Analysis

In Fig. 11, the pattern of the HSS torque is exactly the same as the LSS torque graph, the difference in magnitude is related to the gearbox transmission ratio.

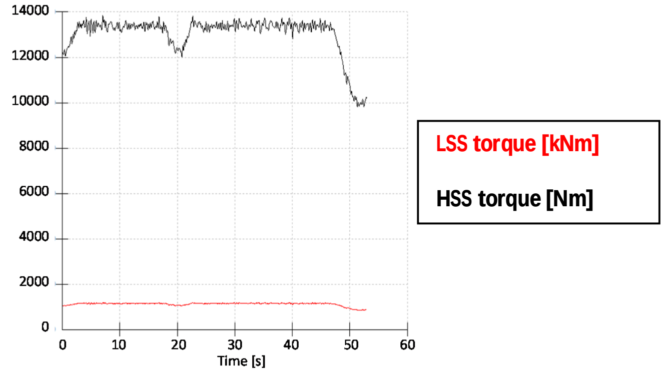

Figure 11. Low (LSS) and high (HSS) speed shaft torques

After 3 s, the pitch control tries to maintain the torque constant at around 1.18 MNm. It is found that the response of the torque to the control strategy displays a fluctuation problem, probably due to the pitch actuator delay. From 18 to 22 s, a torque reduction is observed due to the wind speed reduction below the rated value from 13 to 17 s. This torque loss takes a few seconds to be recovered probably due to the large inertia of the rotor. After this, the pitch control proves to be efficient even with the presence of gusts during the simulated period.

The LSS and HSS torques are plotted on the same graph and in the same scale where it can be seen that the magnitude of the LSS torque is much larger than the magnitude of the HSS torque. Therefore, the LSS mechanical design must be very selective since it will be exposed to very high torque changes and, therefore, higher fatigue loads.

2.2.3 Analysis of the blades and tower degrees of freedom

The blade root M_x, M_y and M_{xy} bending moments as well as the blade root torsional moment M_z are shown in Fig. 12. Once again, the qualitative behavior of the blade root bending and torsional moments is similar to the one verified during steady state regime. The main difference lays on the mechanical stress frequency. It was also found that the bending moment M_y showed the same amplitude for both regimes while the M_x moment is about 5 to 6 times larger in the transient regime.

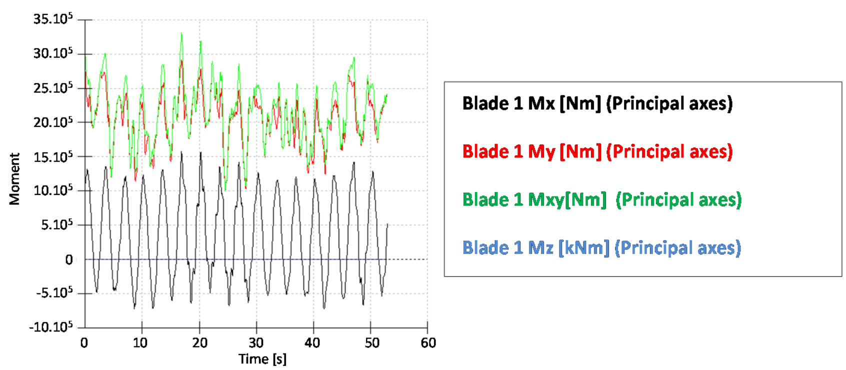

Figure 12. Blade root bending and torsional moment

The M_y tower load increases up to the rated wind speed and then falls at higher wind speeds due to the pitch control, as shown in Fig. 13. The qualitative behavior of the tower bending moment is similar to the one verified during steady state regime.

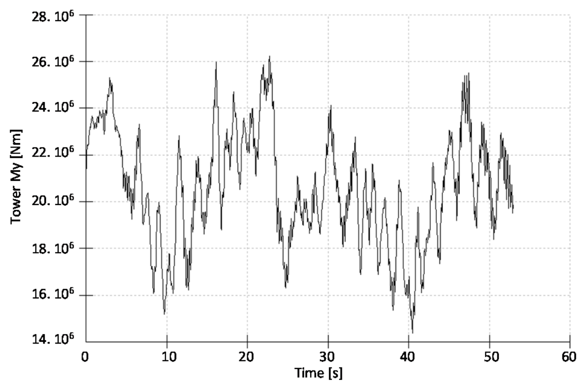

Figure13. M_y (fore-aft) tower bending moment

3. CONCLUSIONS

In this work, the behavior of a variable speed variable pitch wind turbine was simulated by an aeroelastic code for both steady and transient regimes. The loads on different parts of the wind turbine were analyzed.

It was verified that the pitch control proved to be of great importance for the performance of the analyzed wind turbine. For wind speeds above the rated speed, it is necessary to pitch the blades progressively towards feather in order to keep the power output constant, reducing the power coefficient and avoiding excessive turbine loading by reducing the thrust forces acting on the turbine. For the analyzed parameters, the pitch control was generally found to be efficient in reducing the mechanical stress for wind speeds above the rated speed.

The results for the analyzed loads show that they present similar patterns for both steady and transient regimes. The main difference between the results of the simulations refers to the frequency and amplitudes of the simulated stresses and displacements.

The results obtained in this work showed that the proposed procedure was found to be efficient in analyzing the dynamic behavior of the wind turbine.

4. ACKNOWLEDGEMENTS

The authors would like to thank Petrobras which funded this research through the project P&D “Aprimoramento de Aerogerador de 2MW para Adequação às Condições Eólicas Brasileiras”, developed under the Programme for Research and Technological Development of the Power Sector regulated by ANEEL (National Electric Energy Agency).

5. REFERENCES

G. L. Guideline for the certification of wind turbines. Germanischer Lloyd Windenergie GmbH, Hamburg, 2010.

GARRAD HASSAN AND PARTNERS. BLADED for Windows, Bladed Theory Manual Version 4.3 (2012). Disponível em: http://www.gl-garradhassan.com/en/software/GHBladed.php. Acesso em: 05. 09. 2013.

Hansen C., 2014. *Aeroelastic load simulation of a 3 MW two bladed wind turbine*. Master Thesis, Hamburg University of Applied Science.

Urbano, R. B., Witcher D., Nim E, Bradstock P., 2014. Advanced Numerical Modeling for Wind Turbine Loads and Dynamics. Design Tools and Loads Analysis Departments, GL Garrad Hassan, Silverthorne Lane, Bristol, BS2 0QD, UK.

Wilson, D. G., Berg, D. E., Resor, B. R., Barone, M. F., 2009. “Combined Individual Pitch Control and Active Aerodynamic Load Controller Investigation for the 5MW UpWind Turbine”. *AWEA WINDPOWER Conference & Exhibition*, Chicago, Illinois.

Wu, B., Lang, Y., Zargari, N., Kouro, S., 2011. Power conversion and control of wind energy systems (Vol. 77). Ed. John Wiley & Sons.

6. RESPONSIBILITY NOTICE

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