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Dynamic structural analysis and fatigue assessment of wind turbine towers

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Abstract. The wind energy has been very promising because it is inexhaustible energy of low environmental impact. Based on the increasing demand on renewable and clean energy, the wind turbine design has advanced significantly in terms of its size and type. In Brazil, considering this advance, the conventional conical steel tower is a predominant type of supporting structure. Proper consideration of all the aspects before mentioned pointed out our team to develop an analysis methodology with emphasis to evaluate the stresses through a dynamic structural analysis of a typical wind turbine supporting steel tower, including the nondeterministic wind actions. Thus, this research works aims to study the dynamic non-deterministic structural response and evaluate the service life of a steel tower to be used as a support for a wind turbine model type MM-92 from Repower. In this investigation, the numerical model developed for the structural analysis of the tower adopted the usual mesh refinement techniques present in Finite Element Method (FEM) simulations and implemented in the ANSYS program. The analysis of the non-deterministic dynamic response of the tower is performed for several wind velocities, having in mind a critical evaluation about the maximum values obtained for the Von Mises's stresses and the service life of the investigated structure. Finally, the results obtained along this study are evaluated and compared with the limit values recommended by international design codes and recommendations.

Keywords: Steel wind tower, nondeterministic wind dynamic loads, numerical modelling, fatigue verification.

1 Introduction

The growing demand for energy in conjunction with technological development, and the quest to obtain pure energy without causing major impacts on the environment, stimulated the development of systems capable of capturing energy from renewable sources, such as wind, tide and the sun. Wind energy has seen great developments in recent decades, transforming small windmills from centuries ago into slender steel towers with the capacity to generate large amounts of energy [1].

Because of the slenderness of these new structural models, it is necessary and extremely important to study their dynamic non-deterministic structural behavior, since these towers face these loads more and more due to their increasing height.

This study investigates the dynamic structural response of a 76.15 meter high conical steel tower, used to support a model MM92 wind turbine from Repower [2], when subjected to non-deterministic wind loads considering velocities of 10 m/s [36 km/h] to 70 m/s [252 km/h]. In addition to the wind dynamic loadings, the loads associated to the weight of the structure and all its components, the forces generated by the rotor, and the effect caused by the release of vortices are all considered in the tower dynamic analysis.

The developed wind turbine tower finite element model considered the soil-structure interaction effect when the dynamic response was investigated. The results are presented based on the maximum translational horizontal displacements and Von Mises stresses. Considering the maximum stresses on the structure, the steel tower's service life was determined following the classic methodology for fatigue damage assessment, based on the use of S-N curves and the Palmgren-Miner linear damage rule [1]. Finally, the maximum displacements and stresses were compared with limiting values recommended by current design standards.

2 Non-deterministic wind load model

Wind is a random and unstable phenomenon, with an inadequate deterministic consideration for its simulation. However, some hypotheses can be considered for the simulation of these loads, the wind flow is unidirectional, stationary, and homogeneous. This implies that the direction of the wind flow is constant in time and space. Its characteristics do not change during the simulation. For this reason, it is necessary to generate functions over time that concern the floating part of the wind. These functions can be generated through a Fourier series using a power spectrum.

In this study, the Kaimal power spectrum was used (Fig.1), as it considers the height "z" to determine the spectral density of the wind. The floating portion is defined by the superposition of harmonic components proportional to the resonant frequencies of the structure and with random phase angles. A frequency range was defined by modal analysis and that one of these harmonics present in the non-deterministic dynamic loading coincides with the structure fundamental frequency, while the others are multiples of this resonant harmonic.

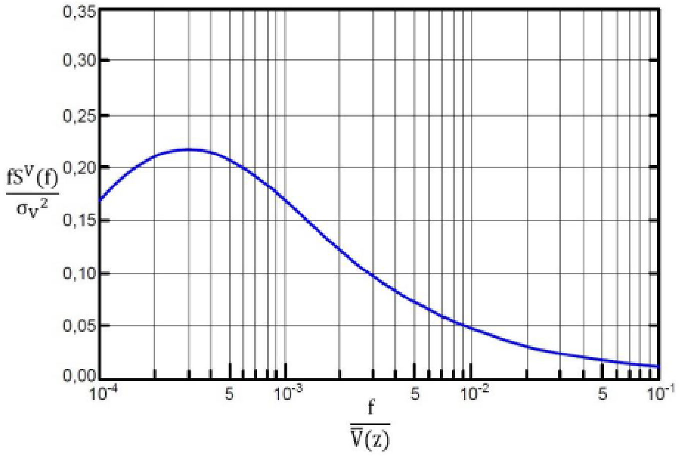


Figure 1. Kaimal wind power spectrum [3].

Using the Kaimal spectrum, the amplitude of each harmonic is obtained, as Oliveira [3] did in his research. Based on a single harmonic function, the floating portion of the wind can be represented. This floating plot is related to the stationary random process with an average of zero, considering the superposition of the harmonic waves, the fluctuations are expressed and the amplitudes of the functions in the time domain, as Oliveira [3] did in his research. The dynamic wind load over time at each node in the tower is expressed by Eq. (1), where C_{ai} is the drag coefficient in region i, q(t) is the dynamic wind pressure and A_i is the frontal area of the contact surface.

$$F(t) = C_{ai}\, q(t) A_i \tag{1}$$

The amplitude of each harmonic is obtained using an existing wind power spectrum density function, based on the Kaimal spectrum. In this investigation, the Kaimal spectrum was adopted due to the consideration of the tower height in its formulation. The power spectrum is given by Eq. (2) and (3) and the friction velocity is determined by Eq. (4).

$$\frac{fS^V(f,y)}{u_*^2} = \frac{200x}{(1+50x)^{5/3}} \tag{2}$$

$$x(f,y) = \frac{fy}{V_y} \tag{3}$$

$$u_* = \frac{k\overline{V_y}}{\ln(y/y_0)} \tag{4}$$

Where f represents the frequency, Sv(f) is the wind PSD in the frequency f, x is the dimensionless frequency, V_y is the velocity at height z, k is the Karman constant, u_* is the friction velocity related to the wind power spectrum density and y_0 is the roughness length. In sequence, assuming that the floating portion of the wind is associated with the stationary random process with an average equal to zero and considering a superposition of harmonic waves, the fluctuations can be expressed as in Eq. (5).

$$v(t)=\sum_{i=1}^{N}\sqrt{2S^{V}(f_i)\Delta f}\cos(2\pi f_i t+\theta_i) \tag{5}$$

Where N is the total number of frequency increments considered in the spectrum, S_V is the PSD of the fluctuating part of the wind velocity, f_i is the frequency in Hz, Δf is the frequency increments in the interval [f_{min}, f_{max}], θ_i is the random phase angle normally distributed in the interval [0-2π] and t is the time in seconds. In this research, it was assumed that the pressures acting on the structural system are calculated directly as a function of the velocity (Davenport's classical model).

The results obtained consider the wind acting on the structure during a time interval of 10 minutes (600 seconds). Fig. 2 shows the variation of the wind load acting on the structure at the same height at velocities of: 15 m/s, 25 m/s and 40 m/s, showing the random character of the wind load regardless of the intensities.

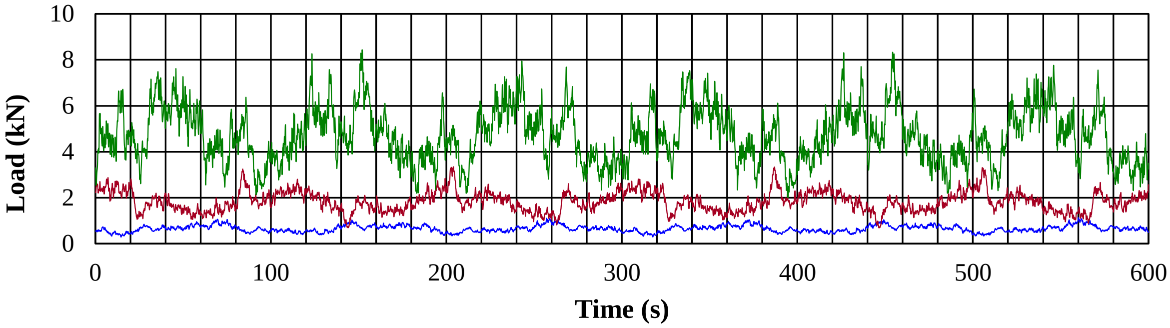


Figure 2. Non-deterministic dynamic forces applied at the top of the wind tower in the time domain.

3 Investigated structural model

The structural model investigated is a steel tower to support a wind turbine, model MM92 by Repower, with a generation capacity of 2 MW of electric energy. Its production range is from wind velocities of 3 m/s to 24 m/s. The tower has a variable thickness along its height, with 30 mm at the base and 12 mm at the top, with a hollow conical shape divided into three parts, as shown in Fig. 3. The foundation is an octagonal shoe inscribed in a circumference of 17 m in diameter and with a constant height of 2.5 m, as shown in Fig. 3.

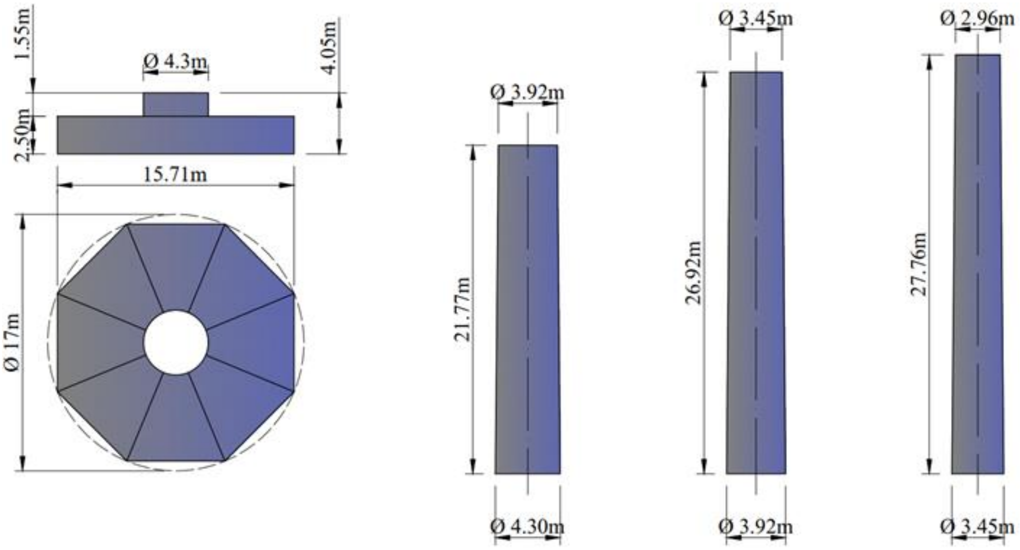


Figure 3. Investigated structural model.

The wind loads acting on the wind tower are: its own weight, loads generated by the rotor, forces from the action of the wind and the release of vortices. Oliveira [3] lists the forces generated by the rotor in two different situations: the first being operational, when the tower is subjected to winds within its working range, and the second, survival, when these velocities exceed its operating range.

4 Finite element model of the wind turbine tower

The numerical model was developed based on the finite element method which for the tower and nacelle was the SHELL 181 shell element from Ansys [5], for the reinforced concrete shoe the solid tetrahedral finite element from Ansys [5] was used and for the soil and structure interaction the spring finite element COMBIN39 of Ansys [5] was used. To correctly represent the interaction between the tower and the foundation, it was necessary to connect the nodes of the tower shell element with the solid nodes element. The spring stiffness was adopted according to the modulus of soil elasticity, and is based on the subgrade reaction coefficient, defined according to Oliveira [3].

The developed numerical model presents an appropriate degree of refinement, allowing for a good representation of the dynamic behavior of the investigated structure. The propellers, rotor and nacelle were represented by a shell element with a density equivalent to their respective masses. The developed numerical model presents 72399 elements, 43339 nodes and 160764 degrees of freedom, as shown in Fig. 4.

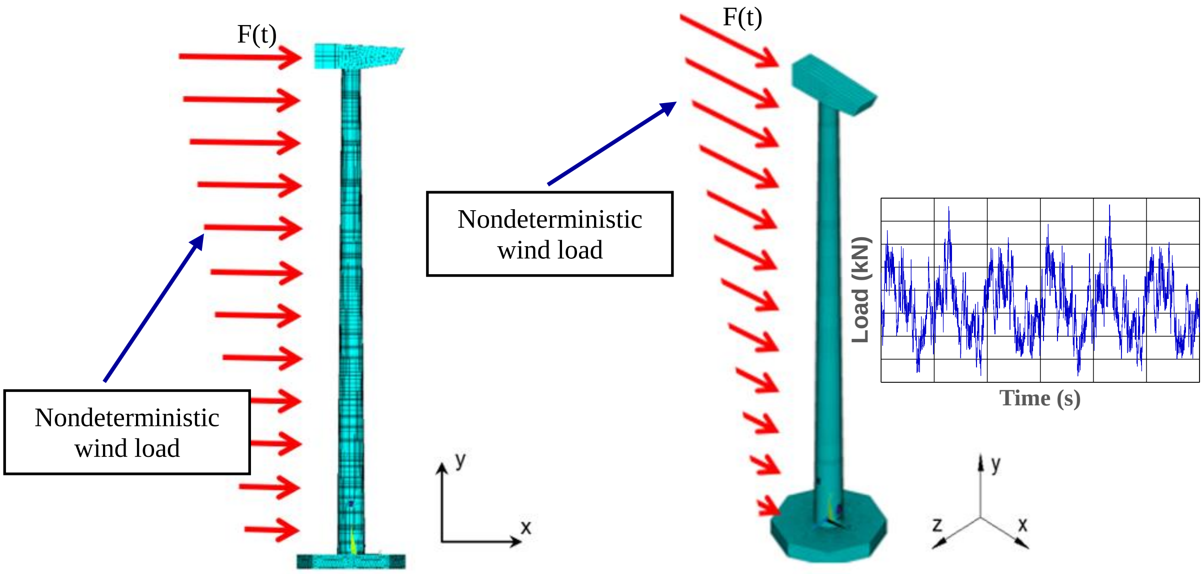


Figure 4. Finite element model of the wind turbine tower [3].

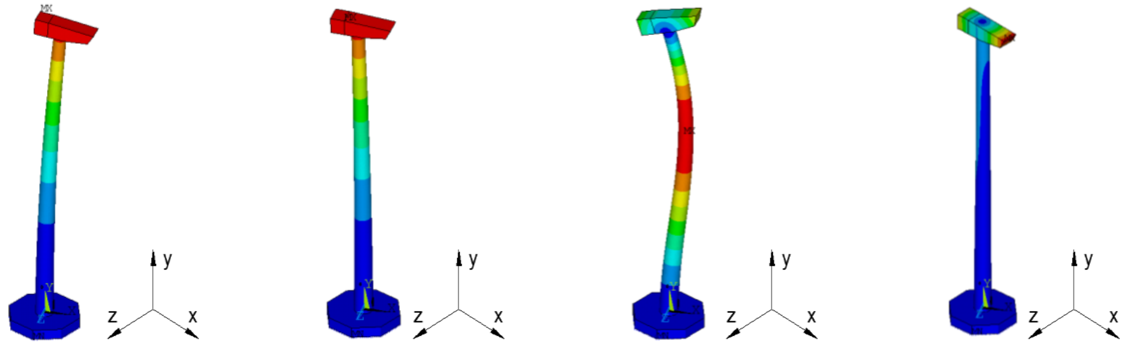
5 Natural frequencies and vibration modes

Natural frequency is a characteristic of the structural system, depending only on its mass and stiffness. When the structure is excited by some external agent, it is possible that the excitation frequency coincides with one of the natural frequencies of the system, when this occurs, the natural vibration mode is excited and amplified, causing the system to resonate. It is necessary that no natural frequencies of the system coincides with the frequencies of the dynamic loads to avoid the resonance phenomenon. Table 1 shows the natural frequencies for the first four vibration modes and the experimental model frequency performed by Rebelo et al [4].

Table 1. Experimental and numerical natural frequencies for the MM92 wind tower.

Natural Frequencies (Hz)	f_{01}	f_{02}	f_{03}	f_{04}
Numerical analysis	0.340	0.342	2.449	2.515
Experimental tests [4]	0.340	0.343	2.767	2.794

It can be clearly noticed from Table 1 results, that there is a good agreement between the structural model natural frequencies calculated using finite element simulations and the experimental results measured by Rebelo et al. [4]. Such fact validates the developed numerical model, as well as the results and conclusions obtained throughout this work. It must be noted that the bending vibration modes were predominant when the dynamic structural behaviour of the wind tower was investigated, as presented in Fig. 5.



1st Mode (f_{01}= 0.340Hz) 2nd Mode (f_{02}= 0.342Hz) 3rd Mode (f_{03}= 2.449Hz) 4th Mode (f_{04}= 2.515Hz)

Figure 5. Vibration modes of the wind turbine tower.

6 Non-deterministic dynamic analysis

Dynamic analyses were performed on the investigated structural model using the ANSYS finite element program [5]. For wind simulation, non-deterministic loads were considered acting in the positive direction of the global X-axis, see Fig. 4. Initially, twenty series of non-deterministic dynamic loading were generated, based on appropriate statistical treatment.

The results of the dynamic analysis shows that the maximum displacements were obtained at the the top of the tower. The wind turbine first vibration mode [f_{01} = 0.354 Hz: bending effects; see Fig. 5] represents the main peak of energy transfer of the dynamic response and this energy transfer become larger as the wind velocity is increased. Figure 6 shows the maximum displacements in the time and frequency domain for the velocity equal to 24 m/s. The horizontal maximum displacement values for each loading series associated to each wind velocity were subjected to statistical treatment [1]. The maximum Von Mises stress values have ocurred at the opening of the tower for all investigated velocities and Fig. 7 shows this maximum stress for the velocity of 24 m/s.

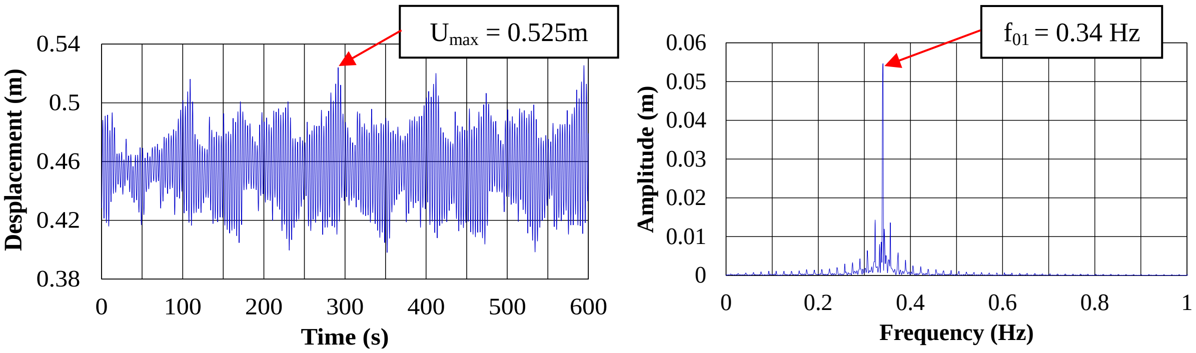


Figure 6. Maximum horizontal translational displacement [V = 24 m/s (86.4 km/h)].

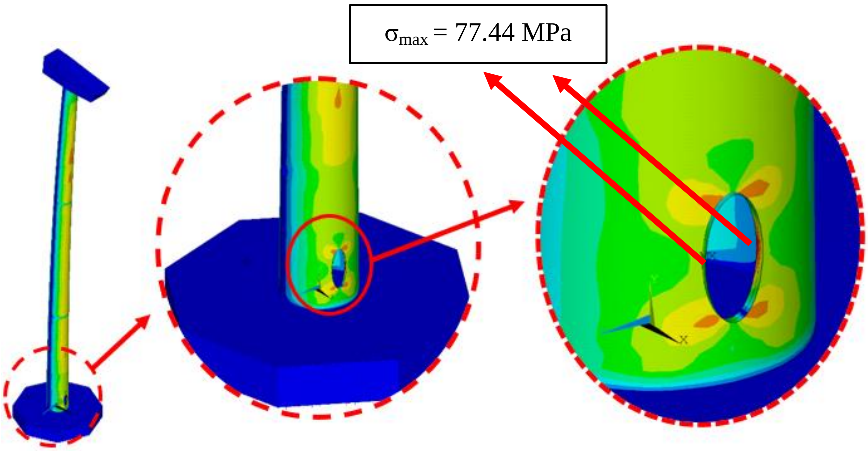


Figure 7. Maximum Von Mises stresses [V = 24 m/s (86.4 km/h)].

In sequence, Fig. 8 presents the results of the dynamic structural analysis for both the horizontal maximum displacements and the maximum Von Mises stress for all investigated velocities. It is interesting to point out that the “jump” in the displacement and stress values between the velocities of 24 m/s [86.4 km/h] and 25 m/s [90 km/h, which also occurs in the same way in the static analysis is related to the modification in the applied loads generated by the rotor from the operational phase to the survival phase.

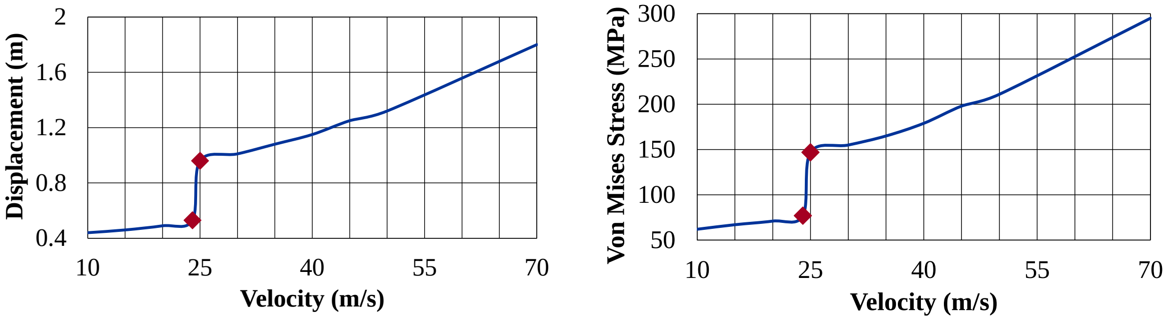


Figure 8. Dynamic analysis results for all investigated velocities (10 m/s [36 km/h] to 70 m/s [252 km/h]).

The Eurocode [7] establishes a maximum displacement value equal to 1.523 m for current metal towers and IEC 61400-2 [8] was used to verify the stress results. It must be emphasized that the maximum stress values obtained in this investigation don’t provoque plastic hinge formations in the wind tower sections. Thus, it can be conclueded that for the usual velocities in Brazilian territory (10 m/s [36 km/h] to 35 [126 km/h]) the wind tower attends the recommended limits. However, considering extremely high velocities, such as hurricanes (70 m/s [252 km/h]), the calculated maximum displacements exceeded this design limit value.

7 Fatigue analysis

It is well known that structures subjected to cyclic loadings are susceptible to the phenomenon of fatigue. This way, having in mind that the non-deterministic wind loads induce the wind turbine tower to stress cycles trhugh the loading and unloading of the structurasl system a fatigue analysis was performed in this investigation. The fatigue analysis was performed following the classic methodology for fatigue damage assessment in structures due to effects caused by actions of varying amplitude, based on the use of SN-type curves and the Palmgren-Miner linear damage rule, based on the use of the Rainflow cycle counting algorithm [1]. Thus, design parameters established by Eurocode [7] were used in order to calculate the accumulated damage and the service life of the structure in years. This way, Fig. 9 illustrates these results showing the service life of the investigated wind turbine tower, in years, for each studied nondeterministic wind velocity profile.

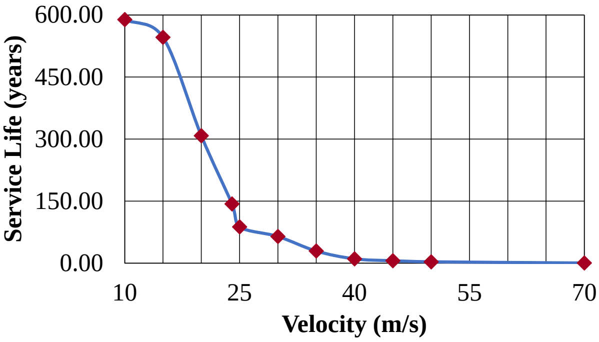


Figure 9. Tower service life for all velocity profiles (10 m/s [36 km/h] to 70 m/s [252 km/h]).

The DNV-GL [6] recommendation presents a design lifetime of 20 years, which is generally assumed as a basis for dimensioning this type of structure. Therefore, based on the results presented in Fig. 9, only velocities higher 40 m/s (144 km/h) do not attend this service life limit. However, it is interesting to point out that the structure is not subjected constantly to wind loads of this magnitude, and for usual velocities (10 m/s [36 km/h] to 35 m/s [126 km/h]) it was concluded that the structural design is viable to be used in the Brazilian territory.

8 Conclusions

This study investigated the dynamic structural behavior of a steel tower to support a wind turbine with a height of 76.15 meters, being submitted to a non-deterministic wind action. The following conclusions can be drawn from the results presented in this work:

1. The study indicates that the structural model presents low values for natural frequencies, with a fundamental frequency of 0.34 Hz. The dynamic structural analysis has shown increasing values of displacements and maximum Von Mises stresses when basic wind velocity increases.
2. The fatigue analysis shows that the service life of the structure decreases as the basic wind velocity increases. However, considering usual velocities (10 m/s [36 km/h] to 35 m/s [126 km/h]) it is concluded that the wind tower structural design attends the recommended design lifetime limit.
3. An interesting point to note is related to the “jump” in the Von Mises maximum stresses and displacement values between the basic wind velocities equal to 24 m/s [86.4 km/h] and 25 m/s [90 km/h]. This fact is associated to the modification in the loads generated by the rotor from the operational phase to the survival phase.

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