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Nondeterministic dynamic analysis and structural optimization of the steel towers design for wind turbines support

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Abstract. Considering the growing demand for electricity and the need to reduce the greenhouse gases emission, the adoption of renewable energy has presented considerable growth in recent years. Having in mind its technological development and competitive prices, the use of wind energy has shown an increasing growth on its installed capacity around the world. In Brazil, a wind potential of 1.78 TW is estimated. This way, this research work aims to perform a dynamic structural analysis of a steel tower used to support a Repower model MM92 wind turbine, with a production capacity of 2 MW. The dynamic analysis is performed based on a three-dimensional finite element model through the utilization of the ANSYS software, considering the soil-structure interaction effect, the wind loadings on the rotor and non-deterministic wind loadings applied on the steel tower. To do this, a wind velocity in the range of survival mode of the turbine is considered, aiming to investigate the tower structural behavior under this condition. After the steel tower nondeterministic dynamic structural assessment, the displacements and stresses values calculated in the steady-state response will be considered for the system optimization, based on the Genetic Algorithms, and using the MATLAB software.

Keywords: wind towers, dynamic structural analysis, structural optimization.

1 Introduction

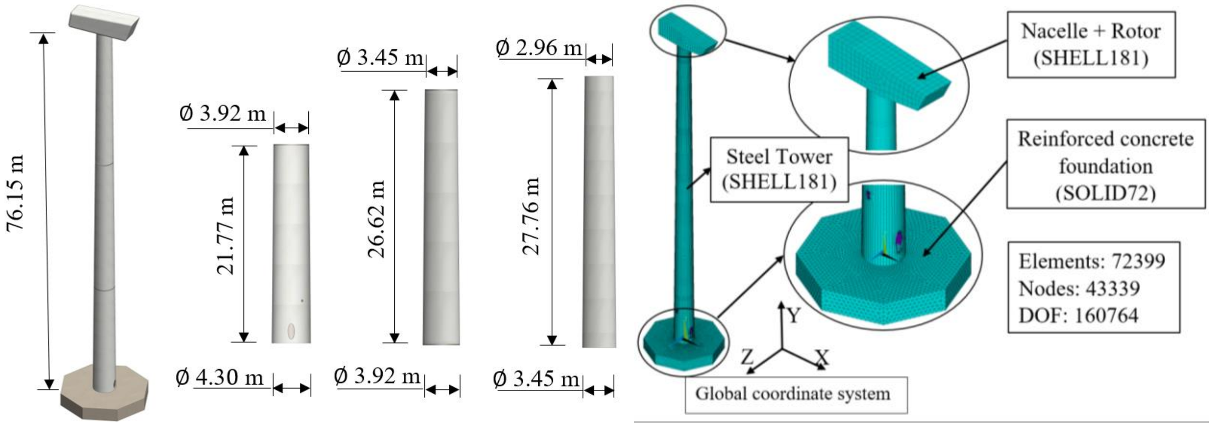
In recent years, considering the technological development and competitive prices, the wind energy installed capacity has been increased significantly around the world. According to ABEEólica [1], Brazil currently has 21.5 GW of installed wind power, with 795 wind farms, more than 9000 wind turbines in operation in 12 states of the federation, with an estimated increase in its installed power to 24.2 GW by the end of the year of 2024. This development of the wind sector in Brazil is justified by the quality of the winds, which present considerable stability, without sudden variations in its velocity.

In the installation of a wind farm, the construction of steel towers for wind turbines support represents a significant part of its total cost. Such structures represent 20 to 30% of the total cost of a wind turbine, thus, obtaining optimized designs represents a valid approach to reduce the cost of installing these devices [2]. According to Silva and Oliveira [3], as wind turbine towers are subjected to several dynamic loadings such as aerodynamic loads, changes in wind direction and gravitational forces, their vibrations have been investigated for many researchers due to relevance of the problem related to wind energy.

In this context, this work aims to carry out a structural analysis of a steel tower to support a Repower MM92 wind turbine with a production capacity of 2 MW, considering a nondeterministic wind load, soil-structure interaction and rotor loads, for further optimization of the structural design using genetic algorithms. For this, due to the nondeterministic nature of the wind's dynamic load, statistical analysis of the dynamic structural response of the steel tower is performed, aiming to achieve the design variables that results onto the structural project with reduced volume meeting the design constraints oriented by the steel tower project guidelines.

2 Structural modelling

The investigated steel tower for wind turbine support is modelled according to Repower [4]. It consists of a 76.15 m tall conical tower with a variable thickness along its height, with 30 mm at its base and 12 mm at the top. On the lower part of the tower there are two elliptical openings for internal access and ventilation. The whole structure is supported by a 2.5 m high reinforced concrete foundation, inscribed in a 17 m diameter circle. The tower is divided into three different conical sections connected by flange-bolted joints. Figure 1a presents the tower model, along its conical sections 's heigh and their respective diameter variation.



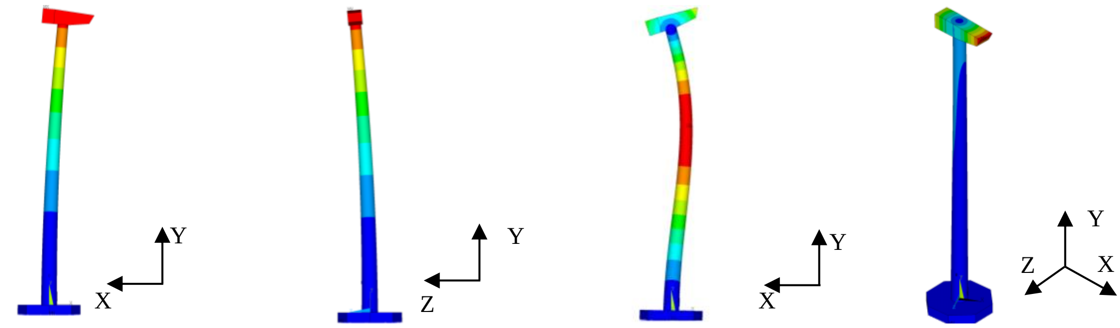
a) Tower and conical sections.

b) Finite element model of the tower.

Figure 1. Steel tower for wind turbine support.

The finite element model for the structure is presented in Fig. 1b. The steel tower and the nacelle are modelled with shell finite element (SHELL181). For the concrete foundation the solid element (SOLID72) is selected. The soil-structure interaction is modelled as an elastic support to represent soil stiffness through a linear spring element (COMBIN14). For this model, a mesh refinement is performed to achieve numerical convergence of the results.

The steel tower is made of S355 steel, with a yield strength of 355 MPa and Young's modulus of 205 GPa, while the foundation is made of reinforced concrete with a yield strength of 16 MPa and a young's modulus of 30 GPa. For the nacelle and rotor, different mass densities are considered to compute the self-weight of the turbine blades (3199 kg/m³) and the generator (2323 kg/m³), resulting in a nonuniform load on the top of the tower.



a) $f_{01} = 0.338$ Hz: bending around Z axis

b) $f_{02} = 0.339$ Hz: bending around X axis

c) $f_{03} = 2.459$ Hz: bending around Z axis

d) $f_{04} = 2.499$ Hz: torsion around Y axis

Figure 2. Vibration modes of the wind turbine supporting steel tower.

The steel tower natural frequencies and vibration modes were determined with the aid of numerical analysis. It can be noticed from the results presented in Fig. 2 that there is an agreement between the numerical results and the experimental data presented in Rebelo et al [5]. It must be noted that the first natural frequency, presented in Fig. 2a, is related to the tower’s first bending mode, thus, it is considered for the modelling of vortex shedding and nondeterministic wind loadings presented in the next section of this work.

3 Wind load modelling

In slender structures, as well as the wind turbine support tower here analysed, the influence of the wind loads its dynamic structural behaviour causes operational conditions that can be harmful to its integrity. Its action, if not carefully observed, can lead to premature failure of the structure, especially in cases where the excitation frequency of the dynamic wind loading matches one of the natural frequencies of the structure. In such manner, this work considers the action of the wind on the structure, considering its dynamic action on the tower, the loads generated by the rotor, and vortex shedding.

3.1 Rotor wind loads

As the wind interacts with the turbine blades, its rotational movement results in centrifugal and centripetal forces, which in turn directly influence the structural dynamic response of the tower. The rotor wind loads onto tower arises from the decomposition of these forces in the directions of interest. In this study these loadings are obtained by the methodology proposed by Umut, Akbas and Shen [6]. Table 1 presents the rotor loadings on the structure, for its operational and survival modes, assuming the global coordinate system presented in Fig. 1b.

Table 1. Wind loads on rotor.

MM92 Turbine	F_X(kN)	F_Y(kN)	F_Z(kN)	M_X(kNm)	M_Y(kNm)	M_Z(kNm)
Operational	181.6	554.6	0.1	367.2	14.1	219.8
Survival	550.3	109.8	0	220	184.5	14.2

3.2 Loads due to vortex shedding

According to EUROCODE 1 [7], the effect of vortex shedding over the structure needs to be contemplated when the ratio between the largest and the smallest crosswind dimension of the structure onto a perpendicular plane exceeds 6. Its loading intensity is given as a function of the critical velocity of the structure v_{crit} and the air mass density (ρ_{air}=1.225 kg/m³). The critical wind velocity, presented in eq. (1), is the velocity related to the structure's first bending mode and is obtained as a function of the average tower's cross section b, its fundamental frequency and the Strouhal number St, adopted as 0.18 for weakly variable conical section.

$$v_{crit} = \frac{bf_{01}}{St} \tag{1}$$

As stated in Oliveira [8], the vortex shedding effect over the tower can be modelled as a harmonic function, whose excitation frequency coincides with the first frequency ω_{01} related to its first bending mode. In this work, the time history for the vortex shedding loadings is modelled as:

$$F_k(t) = \frac{1}{2}\rho_{air} v_{crit}^2 \sin(2\pi\omega_{01}t) \tag{2}$$

3.3 Modelling of the nondeterministic wind loads

Modelling the dynamic wind loading over the tower is a complex and random task. Aiming at modelling the nondeterministic action of the wind, the study here performed presents a mathematical formulation based on the Monte Carlo Method, which is then used to compute the power spectrum density (PSD) associated with wind loads, considering its uncertainties.

The nondeterministic action of the wind along the tower is given as a time varying function, as presented in eq. (3). $\overline{V}$ is the mean wind velocity in the horizontal direction, assumed to be constant and is a function of the height. $v(t)$ is statistically obtained from the mean wind velocity and the height above ground level. This velocity is modelled by a weakly stationary, second order and ergodic random process [9].

$$V(t) = \overline{V}+v(t) \tag{3}$$

The mean wind velocity considered in design is calculated in function of the topographic factor $S_1 = 1$, $S_3 = 1.1$ which is a statistical parameter associated with risk factor and service life required, and $v_0 = 35$ m/s is the basic wind velocity, which is the value related to the area where the state Rio de Janeiro, Brazil is located, as shown on the wind velocity isopleth in NBR 6123 [10].

$$\overline{V} = 0.69 v_0 S_1 S_3 \tag{4}$$

The fluctuating wind velocity portion is decomposed into a finite number N of harmonic functions whose phase angles are randomly defined, in a manner that one of their excitation frequencies coincides with the structure's resonant frequency, whereas the other ones are its multiples and submultiples. In this work, the amplitude of the harmonics is defined by the Kaimal spectrum due to the consideration of the tower height y in its formulation, as presented in eq. (5) and (6). The friction velocity related to the wind power spectrum u_* is shown in eq. (7). Where f is the frequency, $S^v(f)$ is the wind PSD in the frequency f, x is the dimensionless frequency, v_y is the velocity at height z, k=0.4 is the Karman's constant and y_0 is the roughness length.

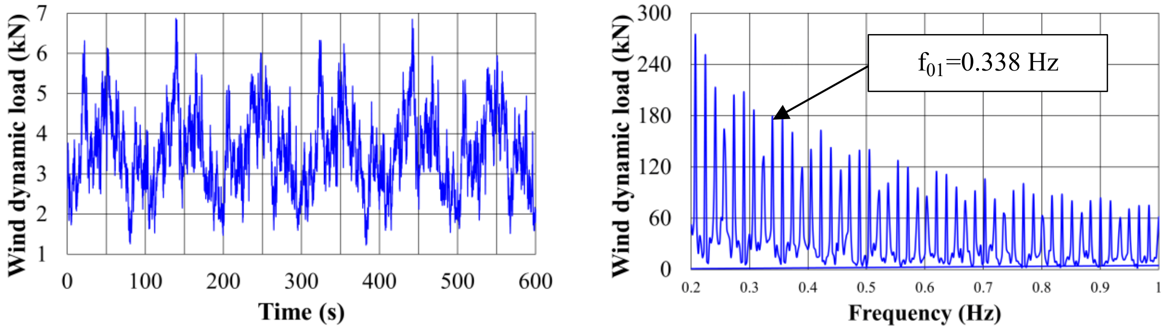
$$\frac{fS^v(f,y)}{u_*^2} = \frac{200x}{(1+50x)^{5/3}} \tag{5}$$

$$x(f,y) = \frac{fy}{v_y} \tag{6}$$

$$u_* = \frac{k\overline{V}_y}{\ln(y/y_0)} \tag{7}$$

The mathematical formulation for the fluctuating portion of the wind velocity v(t) is described in eq. (8), where f_i and θ_i are the random frequencies and phase angles and Δf frequency increment associated with the considered frequency interval.:

$$v(t) = \sum_{i=1}^{N} \sqrt{2S^v \Delta f} \cos(2\pi f_i t + \theta_i) \tag{8}$$



a) Time domain. b) Frequency domain.

Figure 3. Wind dynamic load on the structure.

The wind dynamic pressure acting on the steel tower is calculated as a function of its velocity according to the Davenport's classical method, as shown in eq. (9). The wind dynamic load on the structure formulation is presented in eq. (10), where C_{Di} is the drag coefficient associated with the effective structure's area A_i. Figure 3 presents the dynamic wind load behaviour over time and in the frequency domain.

$$Q(t) = 0.613[\overline{V} + v(t)]^2 \tag{9}$$

$$F(t) = C_{Di} Q(t) A_i \tag{10}$$

4 Structural optimization problem formulation

The optimization problem given in this work aims to reduce the total volume of the steel tower for wind turbine support (objective function). For this, the tower is divided into three different sections, and their top and bottom thicknesses are taken to define design variables array: X = [EA EB EC ED].

The formulation of the optimization problem is oriented by design guidelines of a steel tower to support a wind turbine. Therefore, design constraints related to fundamental frequency, displacement at the top of the tower and maximum stress are considered.

As reported by Sørensen and Dalsgaard [11], for a MM92 Repower turbine, the support tower's first natural frequency should fall in the range 0.281 – 0.341 Hz. According to NBR 8800 [12], the maximum stress value acting on the structure σ_{max} must meet eq. (12), where $\sigma_0 = 355$ MPa is the is the yield strength of the tower construction material and $\gamma_m = 1.35$ is its weighting coefficient. The horizontal displacement constraint at the top of the tower must be as stated in EUROCODE 3 [13], as in eq. (13).

$$0.281 \text{ Hz} \leq f_{01} \leq 0.341 \text{ Hz} \tag{11}$$

$$\sigma_{max} \leq \frac{\sigma_0}{\gamma_m} = 263 \text{ MPa} \tag{12}$$

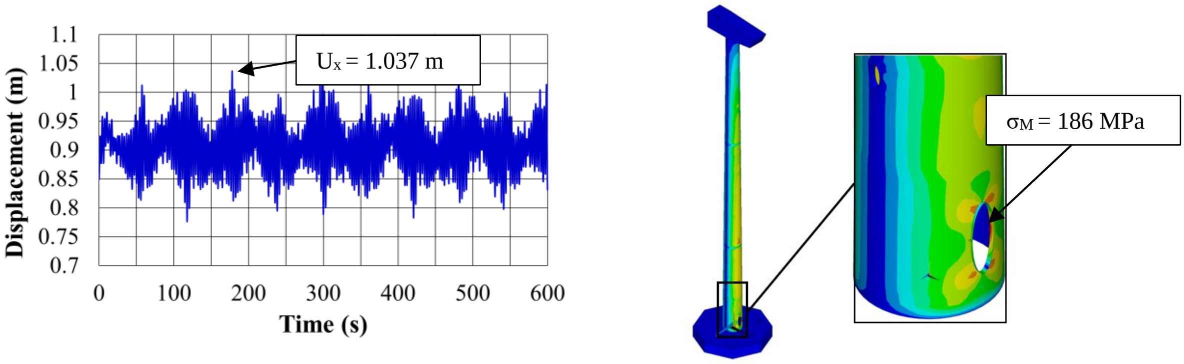
$$\delta_{top} \leq \frac{h}{50} = 1.52 \text{ m} \tag{13}$$

In this investigation, the structural optimization is performed based on the use of genetic algorithms, with an interaction between ANSYS and MATLAB program. For each iteration, MATLAB generates an individual used as input to ANSYS that runs in batch mode to perform the modal and transient analysis of the structure. In each analysis, the dynamic response of the structure is evaluated according to the design constraints presented in eq. (11) to (13). If the individual meets the design constraints, it is selected for the next generation, otherwise, it is discarded. This process is carried out until the algorithm chosen stopping criterion is met.

5 Optimization of the steel tower for wind turbine support

Aiming at a better understanding of the structural behaviour of the steel tower, a dynamic structural analysis is performed considering a random time series of a nondeterministic wind dynamic load. Figure 4a shows the displacement at the top of the tower on time domain, while Fig. 4b depicts the von Mises stress along the structure. Figure 4b highlights that the maximum stress value occurs at its bottom opening, thereby, the stresses in this area are evaluated for the optimization process here presented.

The nondeterministic wind actions on the structure, leads the study to a statistical analysis of the results. This way, to carry out the structural optimization of the steel tower considering its effect on the dynamic response of the structure, ten nondeterministic wind loading series are investigated. The optimal displacement values at the top of the tower, lower opening von Mises stress and the structure fundamental frequency for each of these series are taken for further statistical analysis, thus obtaining the values for the design variables with 95% confidence.



a) Horizontal displacement at the top of the tower b) von Mises stress distribution along the tower

Figure 4. Typical structural response for the steel tower for wind turbine support.

Considering the MATLAB genetic algorithm options, were chosen a population of 120 individuals, a mutation rate of 10 %, a crossover rate of 70 % and lower and upper limits of the design variables of 0.001 and 0.03, respectively. As a convergence criterion, it is determined that the algorithm terminates when the structure volume is not reduced in three consecutive generations. All other genetic algorithms options where set as default.

An optimization considering the static action of the wind on the structure, according to NBR 6123 [10] with basic wind velocity of 35 m/s, is performed for comparison with the results of the nondeterministic action of the wind on the structure. For this analysis, a steel tower that meets all design constraints is obtained, with a volume of 11.61 m^3, EA = 17.3 mm, EB = 15.3 m, EC = 8.6 mm and ED = 6.5 mm.

In the optimization considering the nondeterministic wind action, for each investigated wind load series, the algorithm converged on the fifth generation after 3500 iterations. Table 2 shows the constraint values for each wind loading series, with their mean (μ), standard deviation (σ) and their respective values with a confidence level of 95% (CL95%). Assuming the design constraint values with a 95% confidence level, the displacement constraint has shown a greater influence on the optimization, reaching 97% of the reference value of 1.52 m.

Table 2. Optimization constraints results.

	Initial Project		Optimized Project		
Wind series	U_x(m)	σ_M(MPa)	U_x(m)	σ_M(MPa)	f_{01}(Hz)
1	1.032	184.9	1.339	225.2	0.2995
2	1.021	182.9	1.346	224.1	0.2995
3	1.037	185.9	1.361	225.6	0.2995
4	1.039	186.3	1.399	235.6	0.2941
5	1.035	185.6	1.445	236.6	0.2898
6	1.030	184.6	1.450	239.9	0.2898
7	1.034	185.4	1.333	223.6	0.2995
8	1.019	182.6	1.342	226.5	0.2995
9	1.028	184.2	1.450	238.7	0.2897
10	1.037	185.8	1.431	234.8	0.2898
μ	1.031	184.8	1.390	231.1	0.2951
σ	0.007	1.240	0.050	6.577	0.0049
CL95%	1.043	186.7	1.473	241.9	0.3031

Table 3 presents the values for the best individuals and optimized volume of the steel tower for each wind loading series. The values there presented demonstrate an average steel tower's volume reduction from 17.7 m^3 to 13.4 m^3, with a confidence of 95%, resulting in a volume reduction of 24.3%. If compared with the optimization result obtained considering the static loading [10], these design variables result in a steel tower with a 14% greater volume, with thickness up to 44% greater in the upper section of the tower. This difference in the design obtained is due to the greater displacements imposed by the dynamic action of the wind, showing the relevance of its consideration in the structural optimization of wind towers.

Table 3. Best individuals and optimized steel tower volume.

Wind series	EA (mm)	EB (mm)	EC (mm)	ED (mm)	Volume (m^3)
1	21.15	15.19	14.31	5.54	13.3553
2	21.15	15.19	14.31	5.54	13.3553
3	21.15	15.19	14.31	5.54	13.3553
4	19.99	14.35	13.90	8.46	13.3288
5	19.97	13.73	13.26	10.07	13.2322
6	19.97	13.73	13.26	10.07	13.2322
7	21.15	15.19	14.31	5.54	13.3553
8	21.15	15.19	14.31	5.54	13.3553
9	19.97	13.73	13.26	10.89	13.3685
10	19.97	13.73	13.26	10.07	13.2322
μ	20.56	14.52	13.85	7.72	13.3170
σ	0.001	0.001	0.004	0.004	0.0593
CL95%	21.59	15.72	14.30	11.65	13.4149

6 Conclusions

In this study, a structural optimization of a steel tower for wind turbine support considering the nondeterministic action of the wind is performed. For ten random wind load series, a statistical analysis of the dynamic response of the structure was performed to obtain the optimized values of the design variables and design constraint with a confidence level of 95 %, related to the optimized steel tower volume. This way, the following conclusions can be drawn from the results presented in this work:

1. Considering static wind loading according to NBR-6123 [10], or its non-deterministic action along the tower, the methodology here adopted proved to be satisfactory, since all optimized designs meet the design constraints based on EUROCODE [1], NBR-6123 [10], NBR-8800 [12] and EUROCODE 3[13].
2. When the static action of the wind [10] is considered, the optimization methodology here presented was able to reduce the steel tower volume to 11.62 m^3, representing 34 % of reduction. In this case, the restriction related to the fundamental frequency of the structure showed greater relevance compared to the others, reaching its lower limit of 0.281 Hz.
3. For the nondeterministic wind load, the optimization process reaches an average volume of 13.4 m^3, representing a reduction of 24.3%. Under this condition, the optimized design presents thicknesses in the upper section considerably greater than the values obtained for the static case. This characteristic is due to the greater imposed displacements caused by the nondeterministic wind loading on the structure.
4. Thus, the results here presented indicates that the consideration of the nondeterministic action of the wind is relevant for steel tower for wind turbine support optimization in order to obtain more reliable designs.

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