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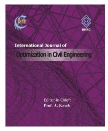

STRUCTURAL ANALYSIS AND STRUCTURAL OPTIMIZATION OF SELF-SUPPORTING TRUSS TOWERS TO SUPPORT A LARGE WIND TURBINE

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ABSTRACT

This article aims to study the self-supporting truss towers used to support large wind turbines. The goal is to evaluate and validate numerically by finite element method the structural analysis when the lattice structures of the towers of wind turbines are subjected to static loads and these from common usage. With this, it is expected to minimize the cost of transportation and installation of the tower and maximize the generation of electricity, considering technical standards and restrictions of structural integrity and safety, making vibration analysis and the required static and dynamic loads, thereby preventing failures by fractures or mechanical fatigue. Practical examples of towers will be designed by the system and will be tested in structural simulation programs using the Finite Element Method. This analysis is performed on the entire region coupling action of the turbine, with variable sensitivity to vibration levels. The results obtained for freestanding lattice tower are compared with the information of a tubular one designed to support the generator with the same characteristics. At the end of this work it was possible to observe the feasibility of using lattice towers that proved better as its structural performance but with caveats about its dynamic performance since the appearance of several other modes natural frequency thus reducing the intervals between them in low frequency and theoretically increase the risk of resonance.

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KEY WORDS: structural analysis; large wind turbines; vibration analysis; self-supporting truss towers; wind energy; finite element method; structural optimization.

1. INTRODUCTION

The Wind energy is a renewable energy that can be used directly or be transformed to other types of energy, such as electricity. The first known use of wind energy dates to the year 3000 BC [1,2] with the first Egyptians sailboats. A few millennia later (s. VII in Persia) the first windmills that would grind grain or pump water appeared. Nowadays, those windmills can be produced with high electrical efficiency, and are called wind turbines. A wind turbine is formed by a set of blades (usually three) connected to a rotor through a gear system, connected to an electrical generator. All this machinery (wind turbine) is placed on the top of a mast or tower where they are more affected by the wind. The length of the blades define the diameter of the area swept by the same and the larger this area is, the greater the power that can generate a wind turbine. One can find everything from small wind turbines of 400 W and approximately 1m in diameter paddle or huge wind turbines of large wind farms of 2,500 kW and 80 m diameter blades.

For small household or agricultural plants the most useful and workable turbines are those with a sweeping diameter of 1 to 5 m, that can generate from 400 W to 3.2 kW. These have an advantage, moreover, that may start at a wind speed lower than the larger, such as sea breezes or Mountain Winds, and produce the most amount of energy. They need a minimum wind speed of 11 km/h to boot (compared to 19 km/h of the biggest), achieve their maximum efficiency at 45 km/h and be stopped with winds over 100 km/h to avoid engine damage or wear or overload [3,4].

Here we intend to study the towers of wind turbines from the preliminary analysis of the velocity profile (turbulent) wind up with about 50m tower base in mountainous regions. Note that the wind speed and turbulence intensity are conditions that dictate the standards of design loads of the towers and wind turbines [5].

From the study of aero-elastic structure (blades / turbine + tower), can be detected excessive vibration levels, which in addition to jeopardizing the proper functioning of the system, in extreme cases lead to their ruin. An alternative to this problem is the installation of passive control devices. A passive control system is summarized for the installation of one or more devices incorporated into the structure which absorb or consume a portion of energy transmitted by dynamic loading, thus reducing dissipation of the energy in the members of the main frame. One of the most common control devices is the tuned mass damper (AMS), which in its simplest form, consists of a mass-spring-damper that acts by transferring part of the vibrational energy to the structure itself. The use of AMS coupled to the turbine to reduce vibrations caused by wind are already being studied, but remain to be detailed aspects such as the robustness of the AMS in relation to changes in the parameters of the system as a whole. The addition of these buffers changes the dynamic analysis of the system requiring a reassessment of the whole blade / turbine + tower. This modification generates a significant change in the dynamic analysis or of the structure inducing feedback phases of interaction fluid-elastic and aero elastic optimization. Eventually, this new configuration will generate the need for further studies on the mechanical and structural reliability [6,7].

Figure 1 details the best region in the Brazil, where one can see the great wind potential. It is observed that the higher the wind speed, the greater the amount of power generated by wind turbines. The minimum thresholds of attractiveness for investments in wind power depend on the economic and institutional contexts of each country, varying in terms of annual average speeds between 5.5 m/s and 7.0 m/s (19.8 km/h and 25,2 km/h). Technically, annual averages from 6.0 m/s (21.6 km/h) already provide favourable conditions for the operation of wind farms [1,6,8].

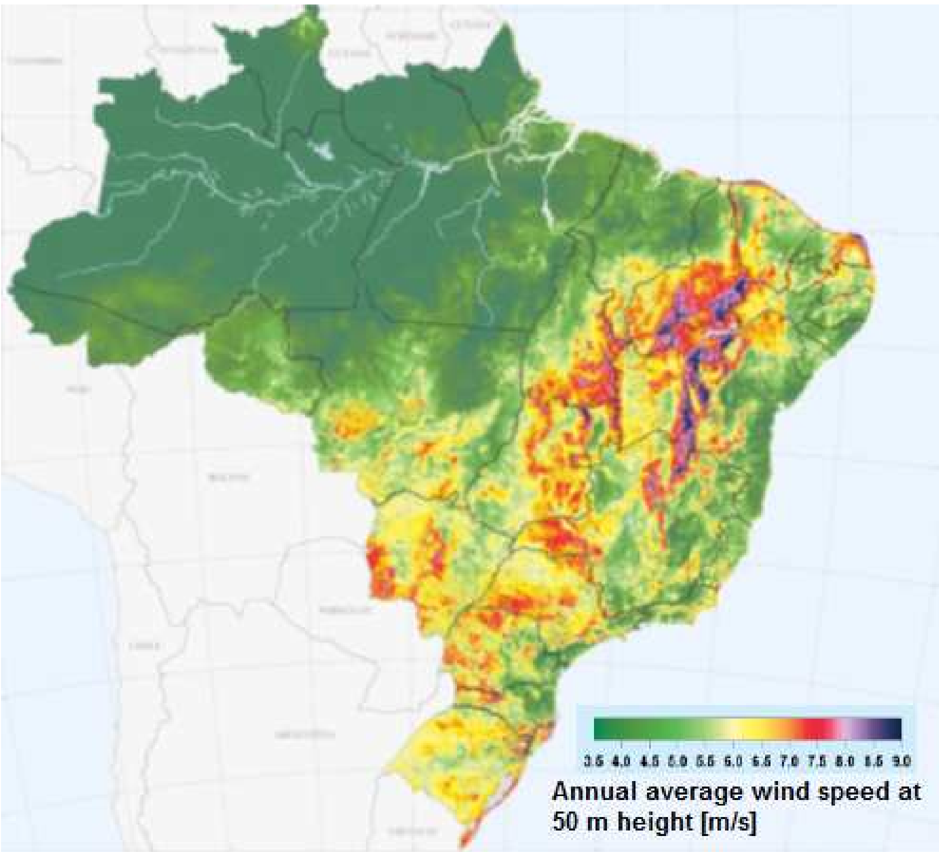

Figure 1. Wind Atlas of Brazil, with some areas selected as most promising ventures of wind farms [1]

2. DESCRIPTION OF THE MODEL IN FINITE ELEMENT

The wind tower lattice steel studied in this article refers to the model to a tower model standard for energy transportation in Brazil, the results of this model will be confronted with tubular tower model. This tubular tower is present in several countries like Spain, Portugal and Germany having a capacity to generate 2 MW of electricity. The model has a shape of a truncated hollow cone divided into three parts in order to facilitate transport and assembly. The first has a height of 21.77 m and base diameter of 4.30m, the second has a height of 26.62 m and base diameter of 3.91m on top. Finally, the third part has a height of 27.81 m in diameter at the base of 3.45 on op. It becomes to a total height of 76.20 m [6,7].

The self-supporting lattice tower used in this study is the initial reference used by towers in Brazil strengthened as wind towers truss designed in some countries, including Germany [8,9].

The model lattice has a square profile divided into two parts in order to increase its bending stiffness and torsion. The first has a height of 48.0 m and a square profile with base edge on the basis of 24.0 m, the second at a height of 28.12 m based on 8.00 m finishing edge on top of the second part with a square profile edge of 6.00. Figure 2 illustrates the divisions of the lattice tower. The lattice tower comprising the feature profile at "L" with dimensions of 44.45 mm x 44.45 mm and a thickness varying according to the voltage levels on the results obtained charging pro-sustained action of the wind [6,10].

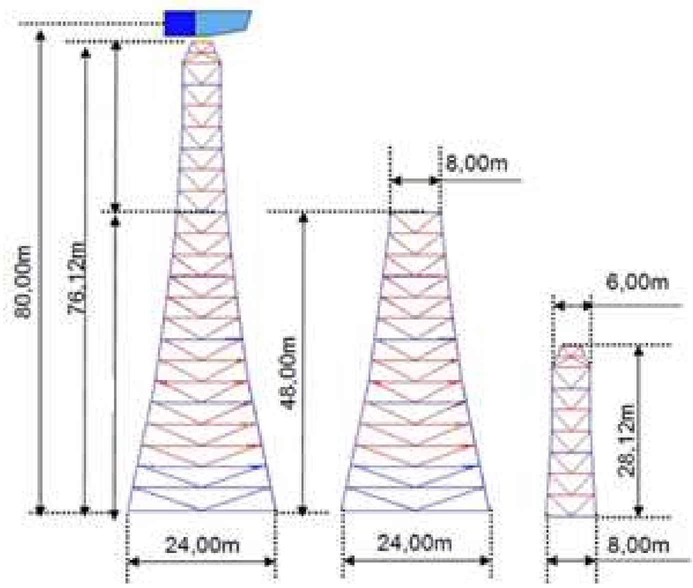

Figure 2. Representation of the lattice wind tower

Until the final construction of the tower used in this work, more than 40 profiles were created and tested until its final outcome was considered relevant as its viability structure.

In Figure 3, we can observe advancement of the project from its conception to the final model of the tower [6,7].

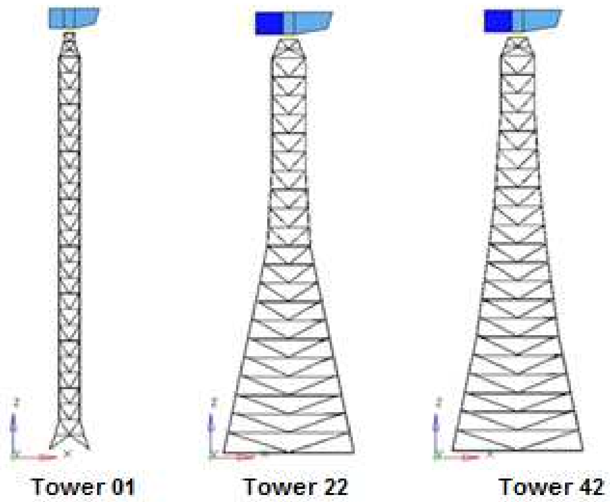

Figure 3. Advancement project freestanding lattice tower wind

Simplifying assumptions:

- Aiming to computational implementation of a mathematical model, through the use of finite element method in order to translate more realistically the effect of wind tower studied in the article were based on the following simplifying assumptions:
- It is the only system of linear material.
- It is considered that binding of parts of the tower does not suffer the effect of rotation, using joints simplified in drive bezel.
- The nacelle and rotor and propeller been simplified calibrated with a material having a density which is its total weight.
- The tower had its base simplified considering the rocky terrain of the study area. In this case a collet were considered rigid base of the tower preventing any rotation and translation on the base.

3. RESULTS FOR STATIC AND DYNAMIC ANALYSIS

As mentioned, this article presents the results in linear static and dynamic analysis. Static analysis aimed to evaluate the consistency of the model in terms of a preliminary analysis and only to confirm the structural viability of the tower. The dynamic analysis, focus of this dissertation, contributed to the calibration of the model by comparing the fundamental frequency, achieved numerically, with numerical values obtained from other studies correlated and validated experimentally.

3.1 Description of the comparative linear static analysis

The nonlinear analysis was performed from the application of displacement in the centre of the rotor tower toward the x axis (wind at 0° project), in the direction of the x axis. Figure 04 illustrates the nacelle positions adopted in this thesis for the application load. This is justified because the nacelle tower has the same effect in any wind direction for a lattice tower. Analyses were performed with a charge equivalent to that used in the work offset reference for comparison. Figure 04 shows the comparison between the two towers in position for comparison [6,7].

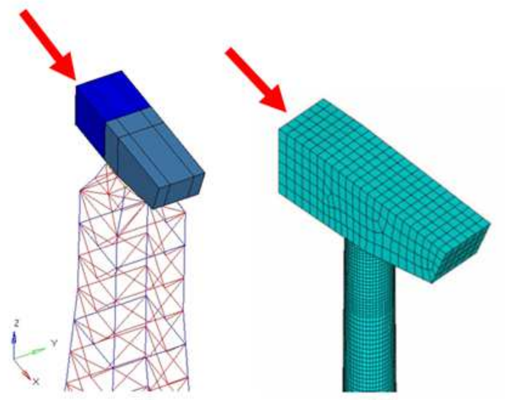

Figure 4. Advancement project freestanding lattice tower wind

3.2 Force applied as a load in the direction of the axis x - 0° wind

Figure 5 shows a graph of load acting on the rotor hub of the tower versus the displacement at the point of application of the load simulating the transmission of the action of the wind on the blades to the wind turbine at position 0°. The chart below shows the behaviour of the towers represented by Figure 4(a) conducted in this work with a load of 1800kN and compared with results obtained from reference Figure 4(b), these generated an offset prescribed.

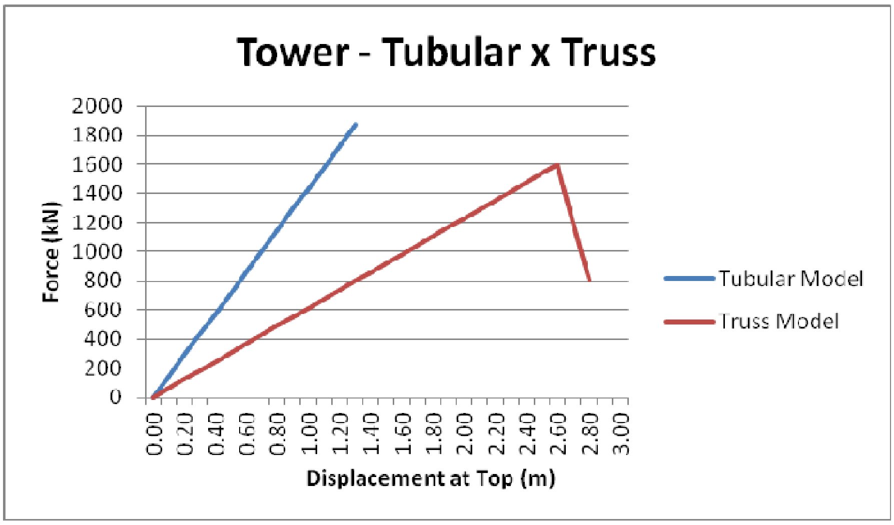

Figure 5. Load versus displacement curve for the wind to 0°

3.3 Dynamic Analysis

Will present the results obtained by computational modelling of the structural model in study for analysis of eigenvalues (natural frequencies) and eigenvectors (mode shapes). Afterwards, it proceeds to a harmonic analysis, aiming to identify the frequencies of the model with the greatest participation in the dynamic response.

Table 1: Presents the results obtained for the lattice tower used as a study in this thesis and compared with the simulation results of the tubular tower above. Fundamental frequency: Comparative Analysis

Frequency	Numerical Analysis (Hz) lattice tower	Numerical Analysis (Hz) Tubular tower	Δ (%)
f01	0,29	0,36	19,4
f02	0,30	0,36	16,6
f03	0,39	2,59	84,9
f04	1,06	2,64	54,8

In Table 1 it can be seen that the results provided by the numerical model are very close, but below the tubular tower model, with differences already expected under the numerical point of view [6,7]. With these results we can see that the lattice tower responds more flexibly and features a large numbers concentrated in low-frequency modes. The comparative results between the two towers, lattice and tubular, are present in Figure 6 to Figure 9.

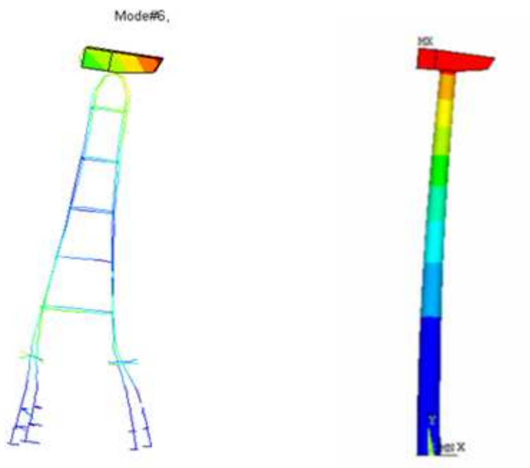

Figure 6. Vibration mode corresponding to the first natural frequency of the structural model: bending in the XY plane

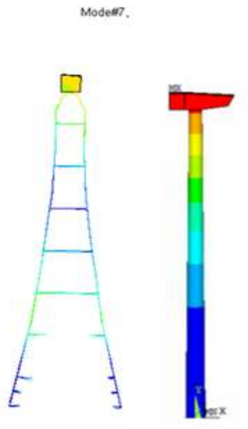

Figure 7. Vibration mode corresponding to the second natural frequency of the structural model: bending in the YZ plane

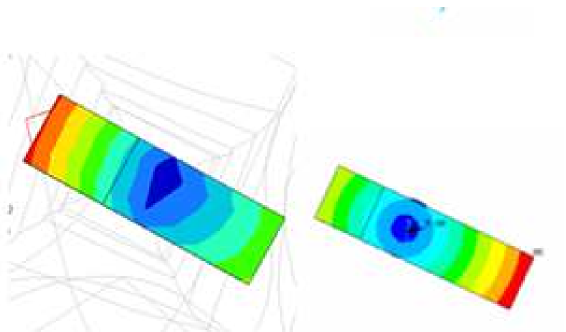

Figure 8. Vibration mode corresponding to the third natural frequency of the structural model: twist

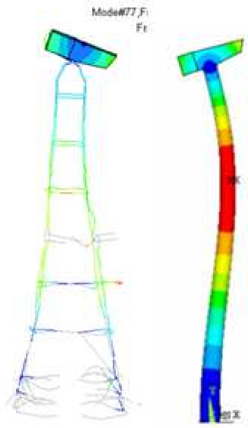

Figure 9. Vibration mode corresponding to the fourth natural frequency of the structural model: bending in the XY plane

Figure 6 to Figure 9 are illustrated the first four vibration modes of the structural model comparing lattice tower with tubular tower model reference work. Figure 6 shows the first natural frequency with a value equal to 0.29 Hz (F01 = 0.29 Hz) associated with a flexure in the XY plane. Figure 7 represents the second natural frequency with a value equal to 0.30 Hz (f02 = 0.30 Hz), associated with the first bending mode in the YZ plane. In Figure 8 the third vibration mode is displayed with a value equal to the natural frequency of 0.39 Hz (f03 = 0.39 Hz), associated with the first torsional mode. The fourth natural frequency illustrated in Figure 9 has a value of 1.06 Hz (f04 = 1.06 Hz) and is associated with the second mode of bending towards the axis XY [6,7].

4. STRUCTURAL OPTIMIZATION

In order to decrease the time needed to prepare the structural truss that meets the requirements of shipping cost, construction and installation, we propose a model for generating self-supporting tower lattice for wind turbines, with computational assistance given some input parameters generates and optimizes the structural design of the towers and foundations based on the internal forces. [3,4] Classifies the structural optimization of tower lattice into sub-problems of size, shape and topology, as in [8,9], having in some cases tools to aid a problem solving multi-objective [10,11,12].

Topological design variables determine an initial structural layout, whereas shape and sizing parameters give the shape and dimensions of structures respectively [13,14]. The optimum shape and sizes of the structure are then found in the later design stage. This is often called multi-stage optimisation. Nevertheless, it has been found that the better design process is to perform topology, shape, and sizing optimisation simultaneously [14,20,36,37].

In the field of structural optimization of tower lattice, various methods have been proposed using Ant Colony Optimization [15], Artificial Bee Colony [14,16], Particle Swarm Optimizer [11,17] and others using Genetic Algorithm [13]. Genetic Algorithm (GA) was proposed by [18,19,20], based on natural selection by Charles Darwin. With that in GA, an individual is a data structure that represents one of the possible solutions to the problem. Individuals are then subjected to an evolutionary process that involves reproduction, sexual recombination (crossover) and mutation. After several cycles of evolution, the population will contain individuals more able [21], with the best solution found in relation to population initially generated. GA has the advantage, the flexibility to adapt to find solutions to the proposed problem without a knowledge derived from problem to deal with, and presenting to the end of the run not only one solution, but several solutions of the problem analyzed. [22,23,24] Presented a solution to minimize the mass in truss up to 940 bars, proving the efficiency of the use of GA in solving this kind of problems and being a great option for finding solutions to multi-objective problems [25,26,27]. Figure 10 is a schematic illustration structural optimization, adapted from [28] for multidisciplinary tower lattice [29,30,31].

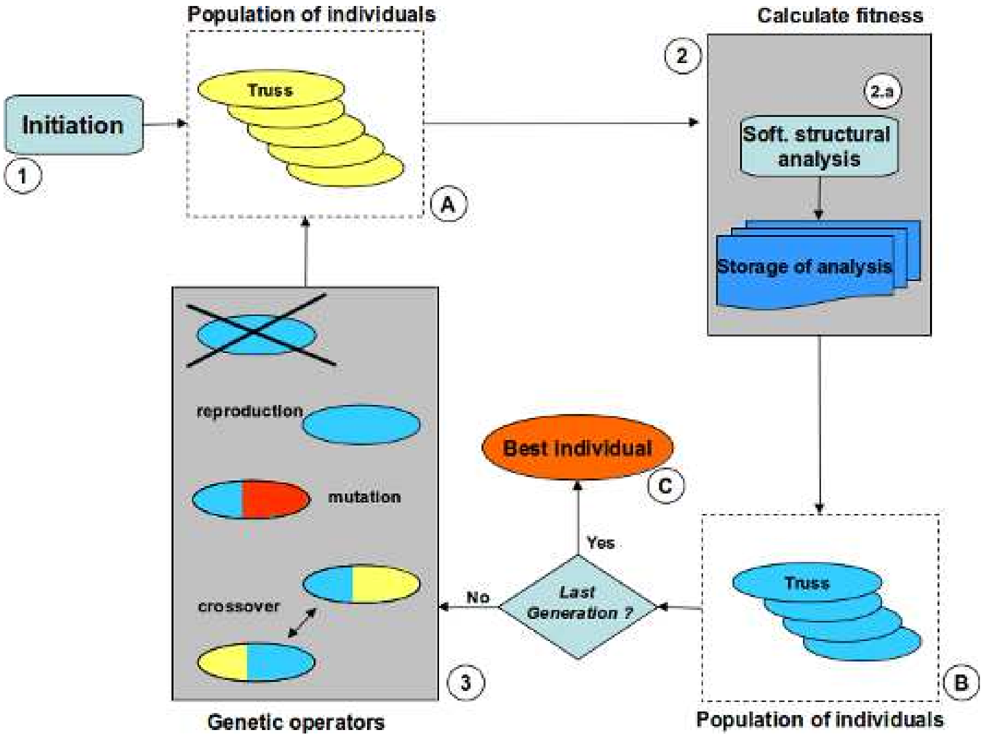

Figure 10. Scheme for structural optimization multidisciplinary of tower lattices

Step 1 - some parameters are reported to the GA for the generation of the initial population of individuals, such as population size, rate of elitism, mutation, and the characteristics related to the location of the truss, and its structural characteristics such as height and size of the truss, maximum cost allowed for the construction, wind speed in the region of the tower installation. - S*tep 2* - runs the method of structural analysis. - S*tep 2a* - for each individual generated, analysis will be performed to check how near to the ideal structure the truss is, taking into account the parameters reported initially and in the media that new structural processes are being generated. They are stored in the database for future structural analyzes generated. In B for each one, the GA returns the fitness value. After checking the suitability of individuals in the population, an inquiry is made whether there all generations of the population initially generated **A**, were evolved. If so **C**, the best individual, the one with the highest fitness value, is selected, the truss is generated with the structural data present in the best element selected. - S*tep 3* - run operations intersection, reproduction, mutation and deletion of individuals so that it formed a new population [32,33,34].

4.1 Truss optimization

The main objectives for the optimization of the lattice is to minimize the weight of the tower, reduce their manufacturing cost, and provide greater ease of construction. Genetic algorithm is used to reduce mass of the turbine tower that among other things optimizes the diameter of the tower considering the compatibility constraints and fatigue design [35,36,37]. Other optimization techniques can be found in the work of [38,39,40,41]. In [34] a structural optimization was performed for the lattice transmission towers which combined the application of the reduction of the mass of the tower with simulations annealing, a decrease of 16.7% of the mass of the tower was achieved.

The cost of production must take into account several factors such as transportation installation, construction and installation of the tower. The equations below are empirical approaches used in the constructions of lattice towers for the Brazilian steel industry. The more complete and detailed is the analysis of costs, the lower the cost for the implementation of wind farms. The cost calculation is basically due to the following factors:

Number of bars(N_m) : the points to note are the material of the bars, its painting, transportation and works in the extremities (holes and welds):

$$C_m = \sum_{i=1}^{N_m} K_m + K_{mm} \rho A_i L_i \tag{1}$$

Where K_{mm} is the cost of steel (\$/ton), ρ is the unit weight of steel (ton/m2), *Ai* and *Li* are the cross-sectional area and length of ith member. K_m is the cost to cut, paint and prepare the bars.

1. Number of nodes (N_n): In this case it is considered the material in the connections, welds, nuts and bolts, assembly and installation:

$$C_n = \sum_{i=1}^{N_n} K_n + j_i hdtf \tag{2}$$

Where K_n is the material and installation cost per bolt, *Nn* is the total number of bolts, *h*, *d* and *t* are the dimensions of the footings, and *f* is the cost of material (reinforcing steel and concrete) for the footings (\$/m^3). The j_i are number of footing per bolt.

2. Number of supports or bases (N_b): Takes into account the construction of foundations for the tower:

$$C_b = K_b N_b \tag{3}$$

Where K_b is the unit cost per tower foundation.

3. Number of types of cross sections of the bars (N_t): In this case, the point to note is the operational cost of tower assembly. Most manufacturers stipulate these values:

$$C_t = K_t N_t \tag{4}$$

Where K_t is the estimated cost to use a specific profile of a manufacturer.

4. Number of bars arriving at a node (N_{nm}): It takes into account the complexity of setting up a node. In this case, the more bars that are connected to a node, the more expensive the process becomes.

$$C_{nm} = \sum_{i=1}^{N_n} K_{nm} N_{nm} \tag{4}$$

Where K_{nm} is the cost to build a bar in a Tower node.

5. Tilt angle of the bars that come on a node (θ_{nm}): It is considered the ease of installation, construction and maintenance of the angle between the bars:

$$C_\theta = K_\theta \sum_{i=1}^{N_n} \sum_{j=1}^{N_{nm}} \sqrt[6]{\left[\theta_{ij}(90-\theta_{ij})(180-\theta_{ij})\right]^2} \tag{6}$$

Where K_θ is the cost of installing bars with an angle and θ_{ij} is the smallest angle between two bars joined at a node.

These values should be subject to the requirements:

$$\begin{aligned}
&\sigma_{i\min} \le \sigma_{ij} \le \sigma_{i\max} \quad , i = 1..N_m \quad , j = 1..lc \\
&-\sigma_i \le -\sigma_i^E \quad , i = 1..N_m \\
&\delta_{ij} \le \delta_{i\max} \quad , i = 1..N_n \quad , j = 1..dc \\
&\omega_m \le \omega_m^* \quad , \quad \text{for some natural frequencies } m \\
&\omega_n \ge \omega_n^* \quad , \quad \text{for some natural frequencies } n \\
&0 \le A_j \quad , j = 1..N_t \quad , \text{for some sections of the manufacturers}
\end{aligned} \tag{7}$$

Where N_m and N_n are the number of members and nodes of the ground structure, respectively: A_j are cross-sectional area of the *j*th member; dc and l_c are the number of displacement constraints and loading conditions, respectively; σ_{ij} is the stress of the *i*th member under jth loading condition and σ_{imin} and σ_{imax} are its lower and upper bounds, respectively; $\delta_{ij}$is the displacement of the *i*th degree of freedom under the jth loading condition, δ_{imax} are the corresponding upper limits; σ_i^E is the stress at which the ith member buckles, i.e. Euler buckling stress; ω_m is the *m*th natural frequency of the structure and ω_m* is its upper bound. $\omega_n$is the nth natural frequency of the structure and ω_n* is its lower bound. Adding all these factors, we obtain the total cost of work (*C*) as

$$C = C_m + C_n + C_b + C_t + C_{nm} + C_\theta \tag{8}$$

In the process of population evolution generated by the GA, each individual represents the structure of a tower, where each individual is inserted into the evolutionary search process to the individual representing the tower lower cost. The objective function of individuals analyzed in each generation, the formula takes into account the total cost of work (*C*) mentioned above.

To minimize the weight of a lattice tower for wind turbines, the structure must follow limits structural [32,33], as in [28], who presented an approach to building towers, obeying standards buckling analysis as ASCE, Eurocode, and AISC. Being according to the author, an approach to building towers of low cost and easy assembly. However, there are several loads [36,37] acting that should be considered as the weight of the wind turbine [35], the force of the wind and the torque of the spades.

In this study, at first a small structure was done, manually made (Figure 11). After that, the optimum structure was generated in Optistruct® by the method of finite elements. In this procedure was also employed a considerable increase of the height of the structure so that it can be used in large turbines. As new structures were made, its weight and construction cost were reduced, as in figure 12 and 13.

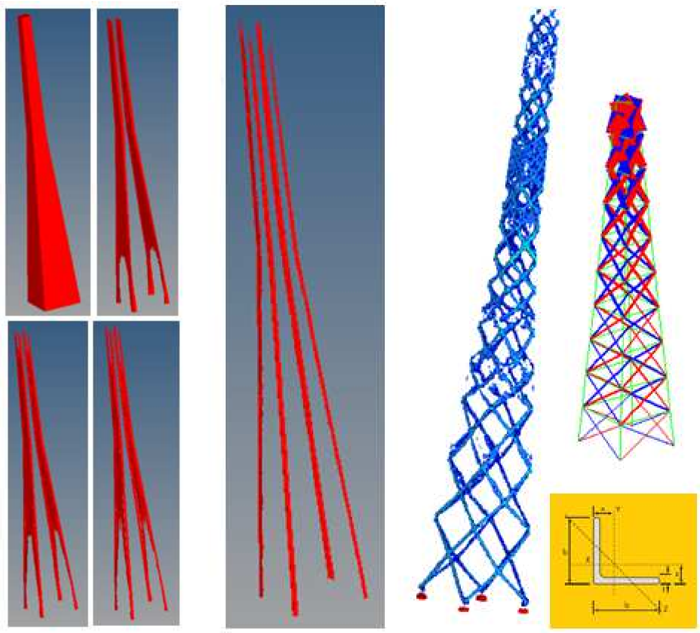

Figure 11. Steps in the optimization process in Optistruct®. In yellow, the profile of bars used

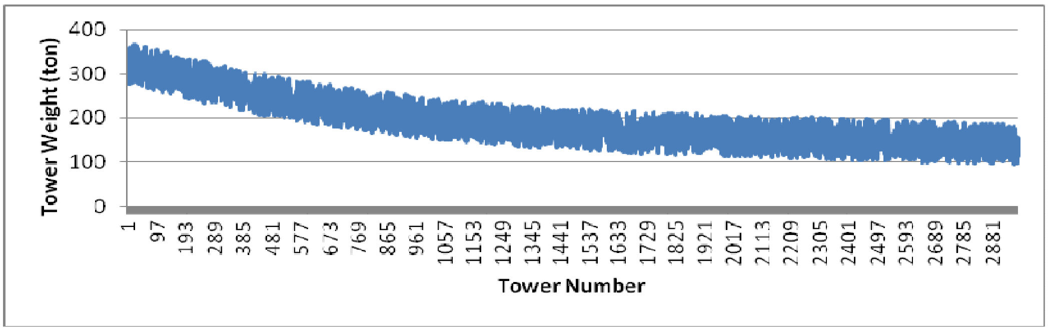

Figure 12. Relation between the weight of the tower and his number

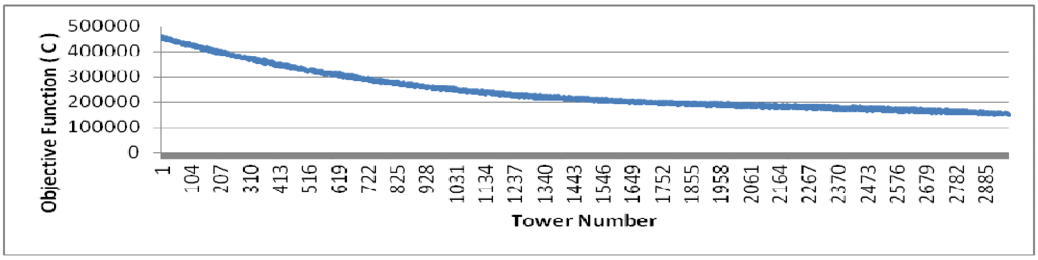

Figure 13. Relation between the price of the tower and his number

4.2 Results

After done the processes presented above, the best structure was named as T3003. The tower was designed for a 1.5 MW wind turbine, to a region where the average annual wind speed is 7 m/s. The tower showed the best relationship between production price and mechanical requirements. Its features are: 122.80 m height, 18.31 m wide base, volume of 12.09 m^3, total weight of 94885.03 kg, 417 nodes and 1164 bars.

The analysis of buckling, deformation and tension were calculated using the programs ANSYS® and SAP2000®. The forces were applied on top of the tower [37]:

- Weight of turbine Fz=-1,067,000 N
- Force of the wind $Fx = Fy$ = 423,373.1152 N
- Torque of the blades $My = Mx$ = 1,176,915.5977 N

The results were a maximum deformation of 2.4226 m at the top of the structure, maximum buckling of 0.72263 m located in the midline of the tower, maximum tension in the bars of 4.8537×10^6N and minimum of -5.4803×10^6N.

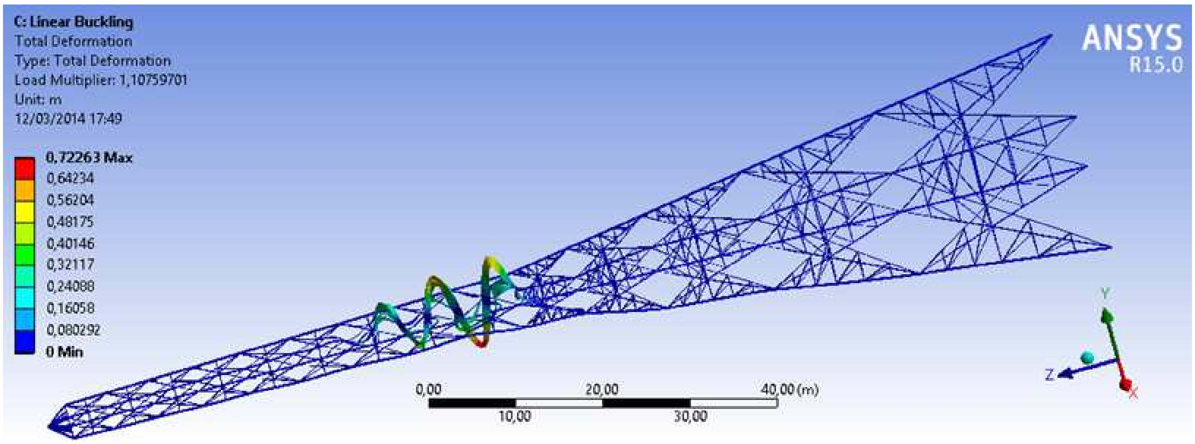

Figure 14. Buckling of the tower due to applied loads in ANSYS®

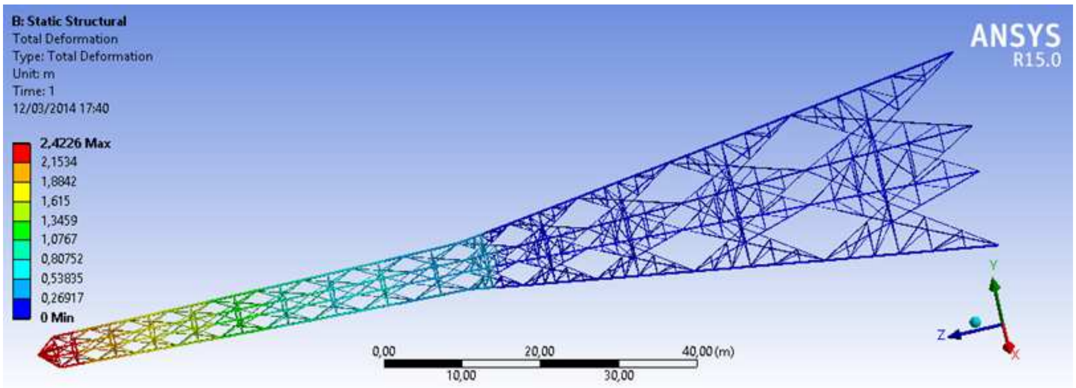

Figure 15. Total deflection due to loads in ANSYS®

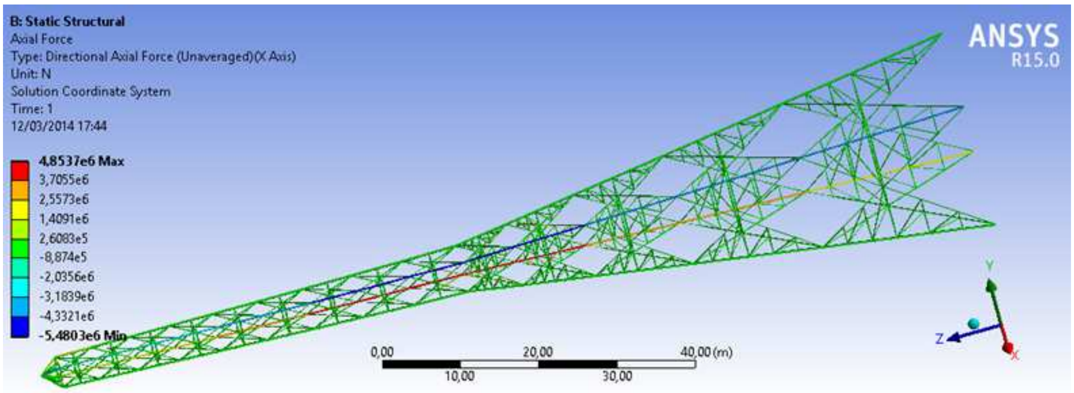

Figure 16. Axial forces in the bars due to applied forces in ANSYS®

The characteristics of the best tower, show the main bars with an inclination of around 80° to the ground and secondary bars forming angles of 30° with the four main sidebars. These values are very close to those found in [23,24] for optimized trusses. In [24] these data are 80° and 30° respectively. These angles correspond to the best relationship between the height of the structure and the cost of production.

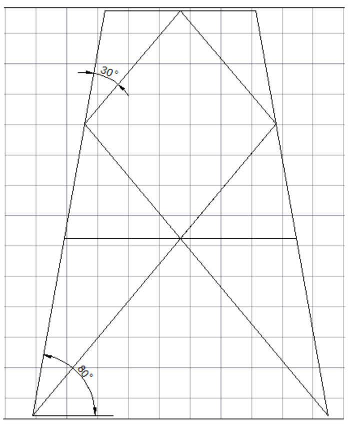

Figure 17. Angle position of the optimum lattice tower

5. CONCLUSIONS

This work aimed to study the static and dynamic analysis of a wind tower lattice according to the standards set by the energy sector. This assessment was carried out through the use of standard techniques discretization via finite element methods and also using other works as a means of validation.

The linear static and dynamic analyses were studied by applying loading to simulate the action of wind on the propeller blades Tower analysed.

This work is divided into two distinct phases. In a first step, linear static analyses were performed on the tower. The next step included the dynamic modelling for various kinds of analyses such as the modal response of the system. In both phases of this work, lattice tower was compared with the tubular towers that are already widely used for this purpose.

The results of the static and dynamic responses of wind towers model were presented in terms of displacement and maximum stresses acting on the towers.

For the two research fronts for validation of a self-supporting lattice tower wind, this was the first to validate the structure of the tower; this was done with some static analysis. The second was to validate the performance of this tower as its dynamic response.

The finite element numerical method proved to be quite useful and accurate in the process of assessing the structural analysis of the tower wind study. Its use was effective in predicting static and dynamic analysis, when compared with results obtained by other studies with the same focus.

It was also observed that no tower collapsed in any of the forty-two (42) models analysed. Buckling or yielding occurred only in some bars whose efforts were distributed to the adjacent bars.

To the front of this second search, the dynamic analysis, it was found that a self-supporting lattice tower responds to the modes at frequencies slightly lower when compared to tubular towers on average 8% lower. Another fact that calls too much attention to the results of dynamic analysis is the large number of modes having a lattice work tower, this may cause a higher risk of occurrence of resonance which can be a problem for lattice towers, and this is because the interval between frequencies is smaller than that of tubular towers. However, the risk may be avoided by acting on changes such as the shape of the profile of trusses.

Soon, lattice towers will be a good option as saving for wind turbine application. It is also an attractive alternative to tubular towers that have typically been used so far.

Another favourable point for lattice towers is the analysis taking into account the low voltages across all components and very safe margin for buckling.

The future of wind power seems to be the large wind turbines, with capacity from 1.5 to 20 MW and blades with 50 meter radius. To support these large wind turbines, tall towers, with more than 100 meters are required. The higher the tower, the greater will be the wind speed and more power will be generated (proportional to the cube of the wind speed power). For these heights, tubular steel towers are very expensive.

To create lattice towers with low cost, one should use the structural optimization to obtain structures with the least possible weight. But the structural optimization is not all; it should be taken into account the cost and ease of construction. This imposes restrictions on the symmetry on 4 sides, number of bars (not very large), number of profiles sections of different size and techniques known to construct lattice towers. That is, the research seeks a tower of low cost, easy construction and installation and not just the use of process of topological optimization to design the towers.

Using structural analysis, it was observed that most of the loads are supported by the 4 sidebars; this justifies the industry to launch a simple profile bracket "L" shaped with dimensions of 250mm to 300mm and thickness of 35mm (or size of 10 to 15 inches from the side and more than an inch thick). These new profiles facilitate the construction and reduce cost.

For secondary bars towers, which has among other functions to solve the problem of buckling, the study revealed interesting profile bracket simple "L" with a very long length (greater than 130mm) and a thin thickness (less than10mm). Something that the steel industry has also worked little. However, this is a good option.

Tall towers are ideal for the use of wind energy in Brazil, which have winds with moderate speed (6-10m/s), no hurricanes, tornadoes and earthquakes. It has vast areas of low land mountains and plateaus. Besides it has a tropical and subtropical climate.

Central regions in Brazil, have areas with good wind incidence during the year with little variation in their direction. Moreover, these areas have lacking in the supply of electricity. This is a promising area for the deployment of wind turbines.

Wind energy is a complement to hydroelectricity, since hydroelectricity is favored with the presence of rain and wind is favored with dry climates.

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