INFLUENCE OF STRUCTURAL CONTROL IN OPTIMIZATION OF WIND TURBINES TOWERS

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Abstract. *The horizontal axis wind turbines are devices that the turbines are conventionally positioned on the top of a supporting tower. These wind turbine towers are flexible, slender and exposed to excessive vibration from the interaction between wind and structure. Thus, a wind tower design should consider the analysis of the dynamic effects of the wind in the tower structure. In this work an analysis of a wind turbine tower with theoretical dimensions will be performed using R13.0 ANSYS software, it is also analysed of the installation of a pendulum passive control system. For both cases it will be performed an optimization study searching for a lower volume in order to evaluate the influence of the control system on the optimal results of the design. This structural optimization of the tower was carried out because of the high tower cost representing 30 % of the total cost of the wind turbine. The tower was modelled with beam elements without the rotor blades and the use of a concentrated mass element at the top representing the wind turbine nacelle.*

Keywords: *Wind turbine, Structural Control, Structural Optimization*

1 INTRODUCTION

Wind turbines are devices designed to convert kinetic energy of the wind into electricity. Wind energy is produced by the air flow in the atmosphere, by a process in which kinetic energy of wind is converted into shaft work, herewith is transformed into electrical energy in the wind turbine generator. In wind turbine towers, it is located on the top the nacele, hub and blades. The high slenderness of this tower adds complexity to its structural design, in this way an appropriate and optimum tower design should consider the analysis of dynamic effects and the geometry (Feijó, 2010).

According to Quilligan et al. (2012), wind turbine towers represent approximately 30% of the cost of the entire wind turbine system, in this manner considerations regarding to optimal design of such towers must be made in order to decrease material cost. Therefore, the structural optimization appears as a suitable technique to assist designers obtaining an optimum design considering geometry.

Wind turbine towers are tall, slender and flexible structures designed to withstand to static loads. However, considerations about the dynamic effects from fluid-structure interaction that the wind exerts on the tower must be considered. In this way wind turbine towers are often subjected to vibrations caused from the wind action and/or from the operation of the turbine generator.

These vibrations are undesirable from the structural point of view and may damage the tower structure due to the high value of the induced structural strain. These vibrations can also cause fatigue of structural elements of the tower, in addition may compromise the security of the entire wind turbine. Once the tower was excited, the structure of the tower spread the vibration energy into blades, turbine and foundations. These vibrations may lead to resonance of the structure, causing excessive deformations or even structural collapse.

To reduce the effects of excessive vibrations, a structural control technique may be used. The structural control tries to reduce energy dissipation demand in structural members under the action of external forces (Lima, 2007). It essentially promotes a change in structure stiffness and damping properties. Changing damping and stiffness parameters can occur through the addition of external devices or by the action of external forces (Avila, 2002). These control systems can be classified as passive control, active control, hybrid control and semi-active control.

In this work, a passive control system was used. It has many advantages such as cost and low complexity. The simplicity of design and execution, coupled with the reliability of these control devices, make them devices frequently used in practice (Zuluaga, 2007). These type of devices are designed to operate controlling structures that vibrates predominantly in a specific range of frequency of interest.

Among passive control systems, there is the pendulum passive control system. The pendulum in its simplest form can be analysed as a mass, spring and damper system, where the pendulum is attached to a vibrating system with the intention of reducing the spread of vibrational energy in structural members under the action of a load or external action.

In this work, the analysis of a wind turbine tower with theoretical dimensions is performed through R13.0 ANSYS software. The instalation of a pendulum passive control system effects is studied. For both cases, it is conducted an optimization study searching to reduce structural volume. The influence of the control system on the optimal design results is analysed.

2 STRUCTURE DESCRIPTION

The wind turbine tower analysed in this work has a circular hollow section. It was modelled by Finite Element Method, as a Timoshenko beam element. The wind turbine has been modelled being a concentrated mass at the tower top to simulate the wind turbine nacelle. "Fig. 1" illustrates the geometry of the tower.

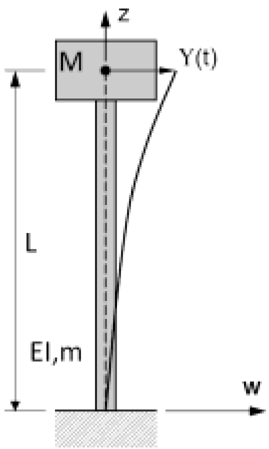

Figure 1. Tower modelled with a concentrate mass element in the upper end. (Morais et al, 2009)

The wind turbine shown in "Fig. 1" was analysed and modelled previously by Murtagh et al (2007) and Morais et al (2009). It was considered a steel tower with geometrical and material properties shown in "Table 1".

Table 1. Geometrical and material properties of the tower

Properties	**Value**
height (m)	60
Width (m)	3
Thickness (m)	0,015
Modulus of Elasticity (N/m²)	2×10^{11}
Density (Kg/m³.)	7850
Concentrate Mass (Kg)	19.876,00

3 NUMERICAL MODEL

The tower was modelled with ANSYS beam finite elements (BEAM188 – beam element of Timoshenko). This element has 6 degrees of freedom and presents linear approximation. The pendulum was modelled as an Euler – Bernoulli beam element, BEAM4. This element has also six degrees of freedom. Using MASS 21 element, a concentrated mass was fixed at the pendulum end. It was adopted a pendulum stiffness of k_p = 1247900 N/m. Between the tower element and the pendulum there is the element COMBIN14 that ensures the system satisfies a pendulum movement.

This model considers internal forces coming from the axial load of the tip mass on the tower top. Also the internal forces caused by a transient loading modelled as a power spectrum of Davenport are considered and finally tower self-weight is also taken into account.

The Davenport power spectrum was also considered on Shzu et al (2015) study, this dynamic excitation is applied to the structure to simulate the action of the wind resultant force into the wind turbine tower. The equations used in the Davenport model for spectral density function of the longitudinal turbulence component in high winds can be found in Blessmann (1995). On this transient analysis a total time analysis of 15 seconds and a time step of 0.1 seconds are considered. An optimization ANSYS R13 algorithm of first order is adopted.

The first order method converts a constrained problem into an unconstrained problem by adding penalty functions to the objective function. The first order method uses gradients of the dependent variables with respect to design variables. For each iteration, gradient calculations are performed in order to determine a search direction, and a line search strategy is adopted to minimize the unconstrained problem (ANSYS, 2012).

This work tries to design a tower with the smallest volume possible in order to reduce indirectly the cost with materials in the tower construction. Thus, the tower volume, as the objective function, is defined by:

$$\mathrm{volume}(x) = \sum_{j=1} AL \tag{1}$$

Where *L* is the height of the tower and *A* the area of the tubular cross-section.

The design variables used in this analysis are the thickness, the internal and the external radius of the top and the base of the tower. The restraints considered in this minimization problem, are the following mechanical inequality constraints:

a) Horizontal displacement on top of the tower.

$$\delta < \delta_{\mathrm{Max}} \tag{2}$$

The maximum displacement constraint was assigned according to the recommendations of the Eurocode 3 (2004). It recommends that the maximum horizontal displacement at the top of the tower must be less than the displacement calculated by Eq. (3).

$$\delta_{\mathrm{Max}} = \frac{L}{50} = 1.2\ \mathrm{m} \tag{3}$$

where δ_{Max} the maximum displacement recommended by the Eurocode 3 and L is is the height of the tower.

b) Maximum equivalent stress, which includes all multidirectional stresses. The Constraint on the maximum equivalent stress is represented by Eq. (4).

$$\sigma \leq \sigma_{\mathrm{Max}} \tag{4}$$

where σ is the maximum von mises stress and σ_{Max} is the allowable stress.

The admissible stress was calculated according to Eq. (5). In this equation, the ultimate strength of steel ASTM - A36 is 400 MPa and SF is the safety factor, which in this work was adopted as 2.

$$\sigma_{Max} = \frac{\sigma_{ultimate}}{SF} \tag{5}$$

Thus the allowable stress calculate in this work was 200 Mpa.

c) Restriction of the minimum thickness, this restriction limits the minimum value of the thickness of the tower shell at the lower commercial thickness of a steel sheet ASTM-A36. This restriction is given by Eq. (6).

$$\mathbf{e} \geq \mathbf{e_{min}} \tag{6}$$

Where **e** is the thickness value and $\mathbf{e_{min}}$ is the minimum thickness of the project adopted as 0.005 m.

4 STRUCTURAL OPTIMIZATION WITHOUT CONTROL SYSTEM

"Table 2" presents the values of the initial design variables and optimal design variables after optimization process under a transient load.

Table 2. Values of the initial and optimal design in the analysis (transient load).

Design variable	Initial project	Optimum project
External Radius (m)	1.5	2
Internal Radius (m)	1.485	1.995
Thickness (m)	0.015	0.005
Stress (m)	270.181	101.01
Horizontal displacement (m)	$3.177 \cdot 10^{-3}$	$2.459 \cdot 10^{-3}$
Volume (m^3)	8.4395	3.7650

In this case, during the optimization process, five iterations (sets) were performed, and the best result of the objective function was obtained in the fourth iteration. The best result for objective function is equivalent to 55.3% of the initial volume of the tower with outer radius of 1.5 m.

In the fourth iteration, where it was achieved the optimum result, the stress reached 101.01 MPa, representing 49.5% of the upper limit for this parameter. The maximum horizontal displacement restriction was to $2.459 \cdot 10^{-3}$ m, representing significant distance from the upper limit of 1.2 m calculated in accordance with the recommendations of Eurocode 3.

Displacement time evolution in "Fig. 2" allows to compare the horizontal displacement at the top end of the initial design of the tower and the displacement of the optimized tower design.

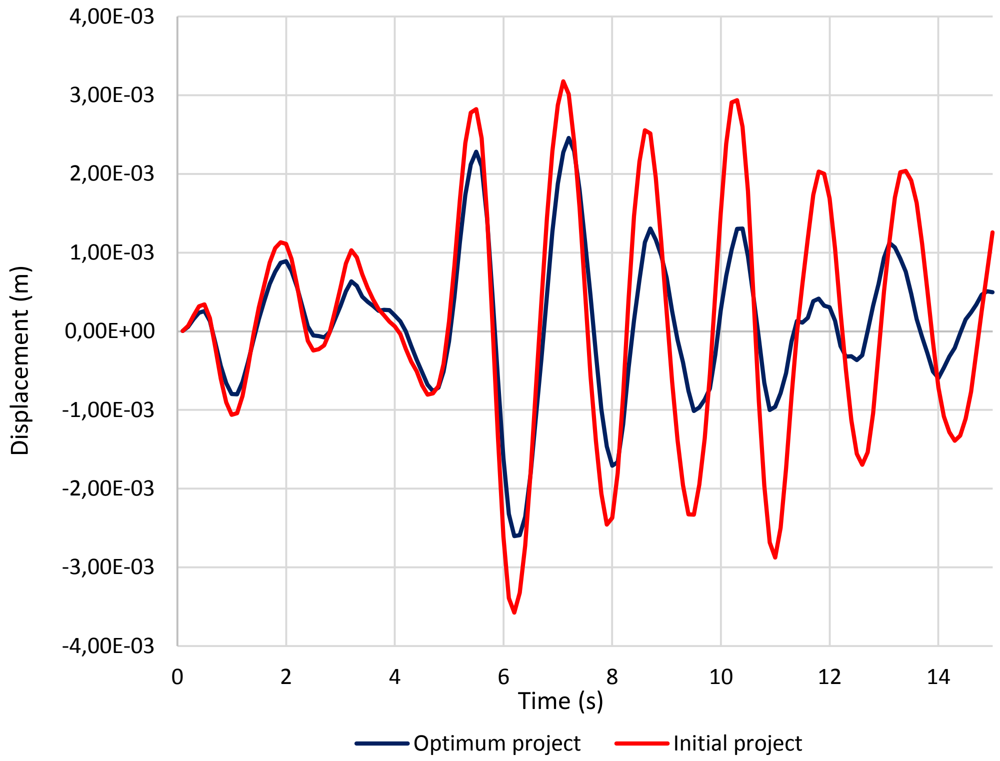

Figure 2. Horizontal displacement time evolution of the original tower design and optimized tower design

The comparison between the two displacement time histories shows a difference between the amplitude of the horizontal displacements of the initial design and optimal design. Although in both designs the magnitude order of the amplitude displacement are equal, in optimum design, there is a decrease in the amplitude of horizontal displacement at the top of the tower.

5 STRUCTURAL OPTIMIZATION WITH CONTROL SYSTEM

In this work, it is studied how a structural control system connected to the wind turbine towers influence the optimization process. The pendulum connected to the tower structure aims to reduce energy dissipation in structural members under the action of external forces (Lima, 2007). The pendulum connected to the structure promotes a change in the stiffness and damping properties of the structure Avila (2002).

Thus, the pendulum was connected to the tower to check the influence of this element in the optimum results of the tower design project.

The pendulum parameters as mass, stiffness and damping must be obtained through appropriate procedures of design that achieve better performance and effectiveness in controlling the structure under study (Lima, 2007). Den Hartog (1956), was a pioneer in obtaining mathematical expressions to determine the optimal parameters to control systems of undamped structures subjected to dynamic excitations. “Figure 3” shows a schematic description of a pendulum TMD attached to the tower.

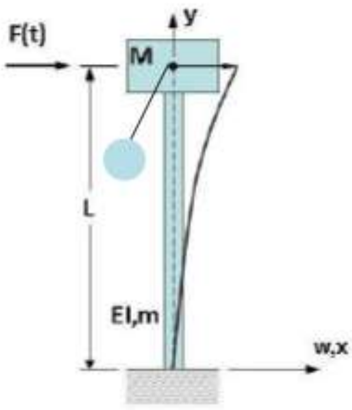

Figure 3. Structure of the wind turbine tower with a linear pendulum attached (Shzu et al, 2015)

The pendulum design parameters used in this study were obtained from Shzu et al. (2015) study, they were calculated through a parametric procedure with the MinMax method suggested by Oliveira et al., (2014). These pendulum parameters are presented in "Table 3".

Table 3. Pendulum Parameters.

Parameters	**Value**
Mass ratio	$\mu = 0.06$
Pendulum mass (Kg)	$M_p = 9198.6$
Stiffness ($\frac{N}{m}$)	$K_P = 1247900$
Length (m)	$L = 4.0$
Damping ($\frac{N \cdot s}{m}$)	$C_P = 9024.9$

In "Table 4" are presented the initial and optimal design parameters without pendulum and with a pendulum connected.

Table 4. Optimum volume with and without control system.

Parameters	**Initial value**	**Optimum value with pendulum**
External radius (m)	1.5	2
Internal radius (m)	1.485	1.994
Thickness (m)	0.015	0.006
Stress (Mpa)	270.181	190.00
Horizontal displacement (m)	$3.177 \cdot 10^{-3}$	$1.128 \cdot 10^{-6}$
Volume (m^3)	8.4395	4.7812

In structural optimization process, the connection of the pendulum in the tower resulted in a reduction of 45.18% of the initial tower volume.

The optimal design of the tower with control reached a volume of 4.4985m^3 (considering that the pendulum connected to the structure adds 0,28273 m^3 to the initial volume), this volume obtained is higher than that obtained in the tower without a control system. However, the maximum displacement of the structure was significantly reduced.

The displacement time history of the excitation is presented with and without pendulum attached to the structure on “Fig. 3”. It can be noticed that uncontrolled and controlled responses have different scales. The uncontrolled displacement amplitude is described on the left vertical axis, and the controlled one is described on the right axis.

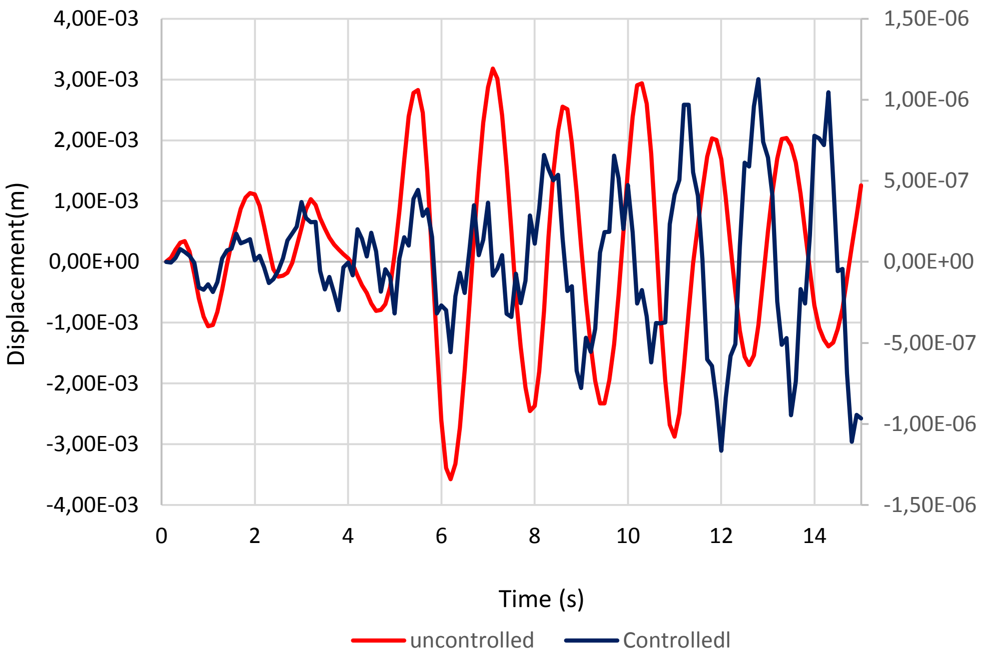

Figure 3. Displacement time history of uncontrolled and controlled structure.

On “Fig 3” it can be noticed that use of the pendulum to control the structure reduced the displacement amplitude a thousand times magnitude. Therefore, the pendulum attached to the structure leads to good vibration response reductions.

6 CONCLUSIONS

In this paper it was analysed the influence of a pendulum passive control system in the structural optimization process of a wind turbine tower. The control system connected to the structure resulted in a representative reduction of horizontal displacement at the end of the tower. However, the pendulum connection to tower resulted in an increase of the stress in the structure of the tower, due to mass concentrated at the end of the pendulum. The result of the stress increase resulted in increasing cross-sectional area of the tower and increases the volume of the tower in relation to the optimal design without pendulum.

Therefore, it is concluded that the wind turbine tower optimization process under study, using the control system in the form of pendulum connected to the structure, results in a lower horizontal displacement, however, causing an increase in the volume of the tower in relation to initial project without control. Taking into consideration the structural safety and the total cost of the wind turbine, it is concluded that the control system connection is structurally suitable for wind turbine towers. Considering that the optimal increasing of the tower volume with the connection of the pendulum is compensated by a reduction of the turbine displacement, resulting in an increased structural safety of the entire system.

7 ACKNOWLEDGEMENTS

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