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THE INFLUENCE OF GEOMETRIC STIFFNESS IN THE SIMULATION OF A WIND TURBINE TOWER

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Abstract. Taking into account that technological advances have enabled increasingly slender projects, it is increasingly necessary to study the influence of second order effects on the behavior of structural elements. When a flexural element is subjected to a significant axial load its elastic stiffness is altered. Wind towers are an example of this, in addition to being subject to bending by the incidence of wind action, they support a large compression load. Item 15.1 of NBR 6118:2014 states that the assessment of the second-order effects occurs when the balance analysis is conducted considering the configuration of the deformed. Thus, the present work aims to study the dynamic response of a wind tower considering the influence of geometric nonlinearity resulting from the weight that the tower supports. The modeling of the structure performed in ANSYS adopts the geometric simplification of the blades of Murtagh et al [1]. To experiment with the computational procedure used in the analysis of the tower, a beam cantilever submitted to a normal static compression load and a transverse dynamic load at the free end was evaluated. The results obtained by the analytical procedure and numerical simulation were compared and, besides to presenting a good agreement with what is expected, shows the influence of pre-tensioning on the bending resistance of a piece.

Keywords: geometric stiffness, wind turbine, prestress.

1 Introduction

With the advancement of research and technology, increasingly tall and slender structures capable of resisting great efforts are delivered to society for the various purposes. However, to enable these new designs it is important to understand the effects that affect their behavior. Such structures are more prone to large vibrations that can reduce their useful life leading to their collapse, in addition, the effects of nonlinearity can significantly alter the results of a linear analysis.

Wind turbines, for example, are structures that fit the profile of slender structures and nonlinear behavior. Nonlinearity can affect the stress-strain relationship, from the elaboration of the constitutive equations of the material, therefore called physical nonlinearity; or change the deformed configuration of the structure. The latter condition portrays the geometric nonlinearity and will be taken here as a focus of analysis.

The effects of nonlinearity have been the object of study in several kind of structures. Mayo et al [2] investigated the applicability of different methodologies to analyze the influence of the geometric stiffness matrix effects on the configuration of the deformed of some numerical examples, to help users choose the one that best suits their problem. Liu and Hong [3] evaluated the effects of geometric stiffness on the stability of rigid-flexible coupling dynamics of an elastic beam subjected to large prescribed displacements. Rodrigues et al [4] analyzed the geometric stiffness in Timoshenko beams considering the terms of high order in the deformation tensor, for this they implemented the geometric stiffness matrix in the FTOOL code, an academic computational program used to solve reticulated problems, and the results were compared with those of the literature with and without consideration of the terms of high *order, as* well as with Bernoulli and Timoshenko beams theories. Their results presented behaviors compatible with the expected.

The study of the effects of nonlinearity is widespread in the scientific world and remains an object of interest in the field of structural analysis. The presence of an axial force changes the stiffness of the structure and consequently the configuration of its deflection. The size of this effect will be quantified for the proposed structures using the classical theoretical formulation and the ANSYS Finite Element software. Thus, it is intended to evaluate the prestress effects through a dynamic analysis comparing the analytical results of a cantilever beam with those obtained using the computational tool ANSYS, in which the second order effect is inserted into the analysis by activating the PSTRESS command. Finally, the PSTRESS effects is evaluated in numerical modeling of a Verner 555 wind turbine with and without vibration control device.

2 METHODOLOGY

The present study was divided into two stages. Firstly, the numerical procedure using the ANSYS computational tool, student version, is tried on a cantilever beam previously presented by Paz and Kim [5]. The beam is 3 meters long and bending stiffness, EI = 10^7 Nm^2. It has a uniform distributed mass of 420 kg/m and a cross section dimension $0.2 \times 0.2\ m$. It is subjected to an axial static compressive load of magnitude 10^7 N and also a dynamic harmonic transverse load of the same value of amplitude at its free end. A modal and harmonic analysis is conducted to evaluate the effects of geometric nonlinearity.

For the execution of the analytical procedure, a routine was written in MATLAB. Only the first nonlinear term is added to the linear formulation. As Paz and Kim [5] explains and exemplifies, for a linear system, the equation of motion is expressed in terms of the mass matrix [M], damping [C] and stiffness [K], Eq. *(1)*

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\} \quad 1)$$

Where $\ddot{u}$, $\dot{u}$ and u are, respectively, acceleration, velocit and displacement and F(t) is the dynamic load applied in the system. The solution to the undamped free vibration problem provides the natural frequencies and vibration modes associated with the system. For the prestress effect to be considered in the analysis, the geometric stiffness matrix, K_G, must be added to the linear elastic stiffness matrix, K, Eq. (2):

$$[K_c] = [K] + [K_G] \quad 2)$$

The second step consist in evaluate the initial stress effects on the tower + nacelle + blades set. It is submitted to an dynamic harmonic load of amplitude 1000 N applied on the meeting point of the three blades. The results were obtained using the ANSYS computational tool. The axial static force is the dead load of the set. The proposed wind turbine is the same of Colherinhas et *al* [6]. The set of blades was modelled as a beam element. They have the same geometry adopted by Murtagh et al [1]. In this proposal, the second-order effects from prestress will be evaluated for the tower with and without the vibration pendulum control device.

3 DESCRIPTION OF THE WIND TURBINE

The Verne 555 wind turbine is a horizontal axis model. The control system coupled to it is of a pendulum model. It is classified as a passive control of the Tuned Mass Damper type (TMD). The mechanism of this system is based on the idea that the damper is tuned at a certain frequency. When it is excited makes the pendulum snore out of phase with structural movement [7].

The structural elements were defined as Timoshenko beam elements, with 6 degrees of freedom per node and linear approximation of the second derivative of displacement. Except for the pendulum control device that was modeled with Euler-Bernoulli beam elements. The connection between the tower and the Pendulum Tuned Mass Damper system control, PTMD, was made using the element COMBIN14, which fix rotation around its longitudinal axis. In addition, a concentrated mass is applied to the free end of the pendulum using MASS21 element. Figure 1a illustrates the assignment of the element types of the structural set.

The wind turbine tower has 60 m height, an external diameter of 3 meters and a thickness of 15 millimeters. The tower and blades have a young modulus equal to 210 GPa, the Poisson coefficient is equal to 0.3 and the density of the tower and the blade material are 7850 kg/m^3 and $2100 kg/m^3$, respectively. Nacelle was considered as a rigid element. The pendulum is 6 meters long. The mass at the end of the pendulum is 3473.3 kg and torsional stiffness and damping as Kp = 1, 247.90 kN/m, and Cp = 9, 024.90 Nms, respectively.

The geometric modeling of the blades in the ANSYS was made using the Murtagh el al [1] simplification. So, the blade is a hollow prismatic beam of retangular cross sections of width, d, 0.8 m; depth, b, 2.8 m and thickness, t, 0.01m, as shown in Figure 1b. Each blade is 30 meters long, L_B.

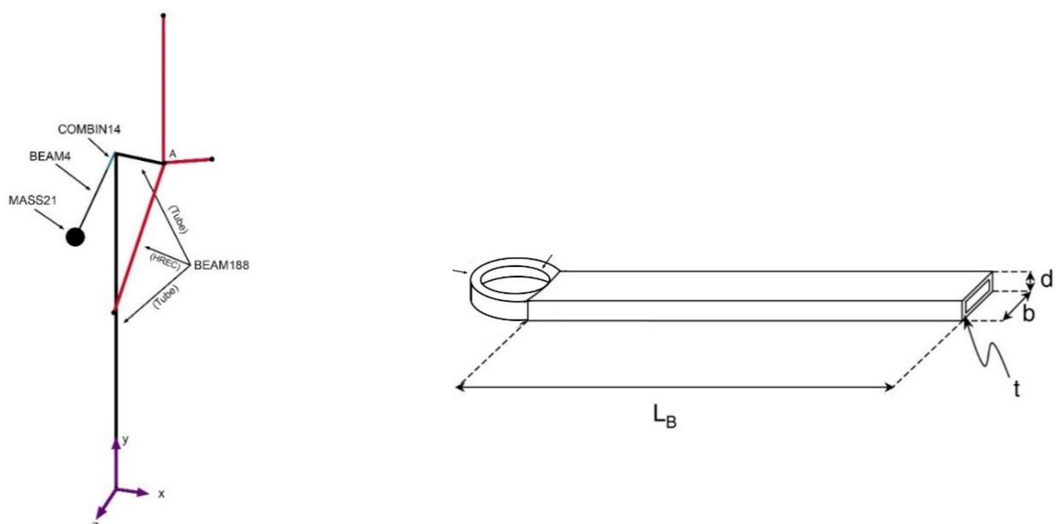


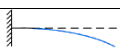
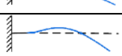
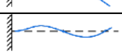
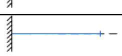
Figure 1. Verne 555 wind turbine. (a) Assignment of elements - ANSYS library; (b) Geometry of the blades.

4 RESULTS AND DISCUSSIONS

4.1 Preliminar analysis

The first step consists in evaluate a prismatic cantilever beam, from analytical exact formulations and Finite Elements Method, as well from computational tool, using MATLAB and ANSYS software, respectively. In the analytical method, the beam has 2 degrees of freedom per node, one translation and one rotation displacement. It was applied a dynamic harmonic transverse load of 10^7N amplitude. To evaluate the second order effect, a static axial compression force of 10^7N was applied. At this stage, modal analysis presents expected prestress effects on the methodologies applied. As can be seen in Table 1, the analysis of the beam without prestress converges to the exact value when the continuum is discretized in a larger number of elements. The discretization in 3 elements was considered to facilitate analytical procedure. Due to the simplicity of the problem, its results, although slightly less accurate, can be taken as satisfactory.

Table 1. Natural frequency of the validation beam with and without the prestress effect

	Natural frequency (Hz)				
	Analytical Method			Computational Method	
	Exact formulation	MATLAB		Ansys	
		Finite Element Formulation - (3 elements)		100 elements	
Modes	No PSTRESS		With PSTRESS	No PSTRESS	With PSTRESS
1 	9.59	9.63	-	9.56	-
2 	60.12	77.85	43.69	58.718	36.91
3 	168.36	171.55	-	159.49	143.27
4 	-	-	212.96	-	222.34

It is verified that the prestress effect changes the beam deflection, decreasing its natural frequencies values. It is also observed that the initial stress effects make the second mode more important. In addition, this condition makes to appear an axial vibration mode that is not perceived in cases without prestress.

Figure 2 shows the Frequency Response Function of the beam with and without prestress obtained using ANSYS. The greatest importance of the second natural frequency of vibration in the prestress model is observed. In this case, the most relevant natural frequency presents a higher value when compared to the most important frequency of the model without prestress.

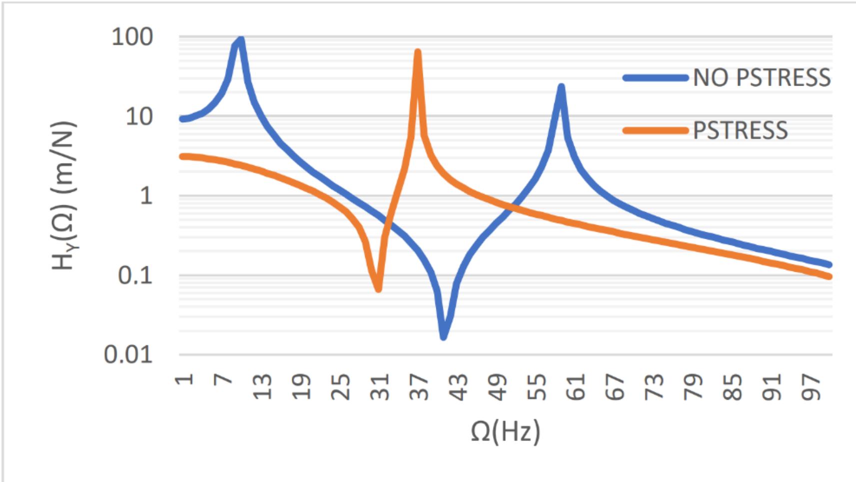


Figure 2. Frequency Response Functions with and without PSTRESS

It is important to evaluate whether these responses are conditioned by the mere presence of prestress or the intensity of static axial load. For this, the prestress value was varied to better understand the behavior of this beam. Table 2 shows the natural frequencies and vibration modes obtained in the modal analysis of the beam for different prestress of compression.

Table 2 – Natural frequencies obtained for the models subjected to different prestress of compression

Frequencies (Hz) for prestress compression load models							
Modes	**0 N**	**1E6 N**	**2E6 N**	**4E6 N**	**6E6 N**	**8E6 N**	**10E7**
1	9.56	7.71	5.09	-	-	-	-
2	58.718	56.88	54.98	50.96	46.61	41.92	36.91
3	15.49	157.93	156.37	153.19	149.96	146.65	143.27
4	-	222.68	222..4	222.57	222.5	222.42	222.34

The existence of axial vibration mode in models with prestress is confirmed. It is noticed that lower values of prestress do not diminish the importance of the first vibration mode, however its presence gently reduces the frequencies vibration values for all modes. This effect is expected since the compression load contributes to the reduction of the elastic stiffness of the problem. On the other hand, high prestress values make setting the second vibration mode more important. Figure 3 illustrates how the variation of prestress influences the change in the deformed structure.

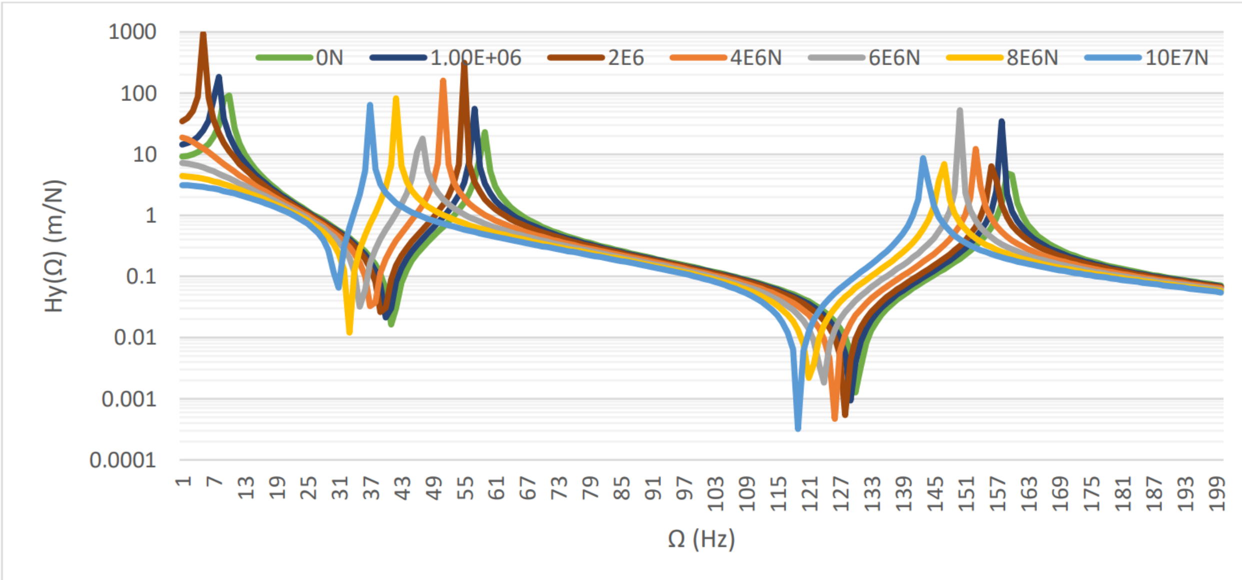


Figure 3 – Axial load response sensitivity analysis

4.2 Verne555 Wind Turbine

The results obtained here are evaluated by the Frequency Response Function of the tower + nacelle + blades set in the frequency range from 0 Hz to 1 Hz, with a step of 0.01Hz, with and without consideration of prestress effect and also with and without the PTMD coupled to the wind turbine. The wind performance was represented by a transverse harmonic load of amplitude of 1000 N acting on the intersectional point of the three blades, point A illustrated in Figure 1a. Figure 4 presents the prestress effects on the Frequency Response Function of the wind turbine with and without control device.

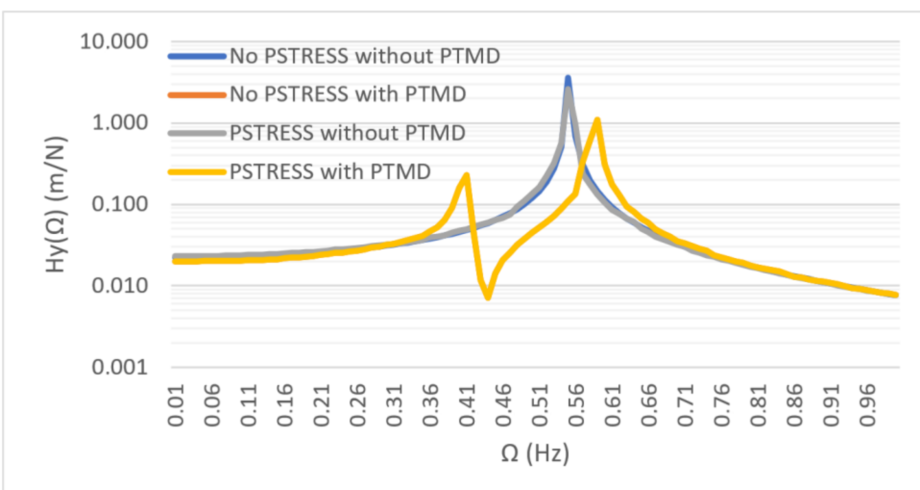


Figure 4. Wind Turbine FRF with and without prestress and with and without PTMD

In the wind turbine it is noticed that the estimated dead load of the tower + nacelle + blades set, approximately 734 *kN*, does not cause significant changes in the deformed configuration of the tower, however it is observed that the amplitude decreases with the consideration geometric nonlinearity effects due to prestress. In the tower with the vibration control device the prestress effects did not demonstrate significant impacts with regard to the deformed configuration, nor the values of the amplitude of the response function.

5 CONCLUSION

The present work demonstrated the importance of assessing nonlinearity in dynamic structural problems subject to static axial loads. The evaluation of a simple element as a cantilever beam was important to point out how these loads and their intensity can influence the behavior of tall and slender structures such as wind towers.

To significantly change the deformed configuration, compression prestress applied to the structure must have intensity in the same order of magnitude as the flexural loads. In these *cases*, the consideration of the geometric stiffness matrix impacts in decreasing of the elastic stiffness of the problem.

In the case of the wind turbine, the geometric nonlinearity effects did not significantly alter the deflection of the tower. However, there is a reduction in the amplitude of the response function in the tower without the control device. In the case of the tower with the control device, the geometric nonlinearity did not alter the structural behavior.

Finally, the present study can attest to the reliability of the computational treatment adopted with the use of the ANSYS Finite Element computational tool at the moment when analytical results were used to experiment and evaluate the computational numerical procedure. In addition, it contributes to future advances in numerical study in this theme to be realized from a better understanding of geometric nonlinearity effects on dynamic problems subject to great vibrations.

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