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ROTOR-BLADES LOADS ON A WIND GENERATOR: DESIGN AND DYNAMIC RESPONSE OF A GUYED TOWER

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Abstract. The design of dynamic loads due to the system rotor-blade action on a wind generator is investigated in this work. Even when considering a perfect laminar airflow, the column causes a disturbance in the flow down the blade. Since this perturbation is produced each time a blade shadows the tower, it produces a periodic variation in the load. The objective of this investigation is to explore the influence that the periodic dynamic on the thrust load produced by the flow perturbation has on the dynamic behavior of the tower. Despite the dynamic is inherently periodic, the actual shape of the variation is unknown and some approximations to the shape obtained by other authors are considered. Some of the parameters of the load variation are unknown, which here will be considered fixed. Finally, the nonlinear dynamic response, in terms of the displacements of the tip of a guyed wind tower is analyzed.

1 INTRODUCTION

The global increase in energy demand, combined with the complexities for the exploitation of oil deposits (and the impact that new drilling methodologies represent on the environment), have compelled the society to the discussion about efficient, permanent and fundamentally, clean alternative forms of energy generation. It is in this context that the energy generation by means of wind turbines has become an attractive alternative, implemented and currently under study and development. Energy production through wind turbines and solar panels is an attractive alternative also in social terms, because it allows to power remote populations, where the connection to the national grid is complex or expensive.

The support structure for the wind turbine consists frequently in a steel tubular column. The wind energy generation require undisturbed wind flows in order to maximize the energy production. Then, the turbine should be positioned as higher as possible. Guyed masts are effectively and extensively applied as support structures for telecommunication equipment as a natural evolution to the monopile towers. In this context, guyed alternatives to the traditional column are studied to improve the structural behavior and reduce the support structure costs for wind turbines (Jespersen and Støttrup-Andersen, 2019).

An installed wind turbine has two characteristic loading conditions throughout it lifetime:

1. The loads acting when the wind is above the operation threshold, which are mainly environmental forces that arise from wind and waves (for offshore turbines). Since the wind velocity is high the turbine is not rotating.

2. The loads from the rotating turbine in the starting and operative regimes. Since the wind velocity on the nacelle is between 3 m/s to 25 m/s (Villalobos Jara, 2006), the wind load acting on the column is low and the thrust load due the interaction of the rotating blades with the wind field becomes the main action on the column.

Then, there could be, at least, three aspects to consider while analyzing the wind load acting on a generator: 1) The model of the dynamic of the wind load, that should be treated as a stochastic field (usually considered by means of a static wind profile), 2) the wind load that, received by the blades is then transferred to the column in a) operative condition (the blades are rotating) or b) while the blades are not moving and 3) the shadow effect that the blades produce to the wind field each time the passed in front of the column.

Despite that the periodic influence of the shadow effect on thrust force of the rotating blades on the column have been reported in technical bibliography (Gasch and Twele, 2011) and other authors have found its influence in complex fluid-structure interaction studies as in Gebhardt et al. (2010), there is not a clear description of dynamics of this loading. Then, dynamic studies of wind turbines are frequently conducted by adding a sinusoidal dynamic variation considering simply the frequency of rotation of the turbine as frequency of the loading, as in Haldar et al. (2018).

In this work, the design of the dynamic loads due to the system rotor-blade action on a wind generator is investigated. The objective of this investigation is to explore the influence that different approaches for modelling the periodic variation on the load has on the dynamic behavior of the tower. Since some of the parameters of the load variation are unknown, here will be considered by observation of the curves obtained by other authors. The nonlinear dynamic response of the different load models is then analyzed considering a guyed support column.

2 ROTOR THRUST LOAD MODELS

The trust load that the rotating rotor blades transfers to the column on operation regime is described by the formula:

$$F_b = 0.5 * \rho_a * \pi * R_T^2 * V_{Hub}^2 * C_T(\lambda_s), \tag{1}$$

where ρ_a is the air density (1.23 kg/m³ at 1 atm and 15ºC), R_T is the rotor radius (in this study is considered 75 m), V_{Hub} wind velocity at the hub height (in m/s) and C_T is the thrust coefficient, which used to weigh the proportion of wind energy pressure that is converted into forces acting perpendicular to the plane of the rotor. The most important parameter to calculate C_T is the ratio λ_s between the blade tip velocity $V_R * R_T$ and the mean wind velocity at hub height $\lambda_s = \frac{V_R * R_T}{V_{hub}}$. Different curves can be obtained for C_T, depending on the blade configuration of the wind turbine.

The wind mean velocity at hub height V_R is between 3 m/s and 25 m/s (Villalobos Jara, 2006), which are the usual minimum and cut operative velocities respectively for 3-blade wind turbines. Regarding the rotor velocity, the operative range is 12-30 RPM (Gasch and Twele, 2011).

As an initial exploration, in this work are adopted the values $V_{Hub} = 12$ m/s and $V_R = 15$ RPM used in Villalobos Jara (2006). Considering R_T=75 m, $\lambda_s = 9.82$, which according with Figure 1 give C_T ≈1.03.

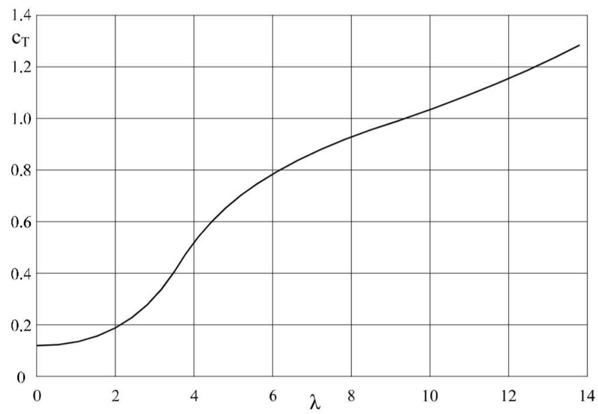

Figure 1: C_T vs λ_s curve, used to obtain the thrust coefficient C_T (Gasch and Twele, 2011).

With Eq. 1 is possible to obtain the aerodynamic force that the rotating blades -subjected to a laminar wind flow perpendicular to the rotor- transfer to the support column in the direction of the wind flow. It worth mention that Eq. 1 does not consider the presence of the column. The column is a physical obstacle, that create a shadow effect to the air flow, which modifies the aerodynamic forces in the blade that is passing in front of it. This effect only appears while a blade move in front of the column. Then, in the common 3-blade configuration used nowadays, it produces a periodic variation in the thrust load with a period of one third the period of rotation of the rotor on a given moment. The breakage of the wake produce a decrease in the thrust force approximately during the time that the blade is moving in front of the column. Also, according with the numerical findings in Gebhardt et al. (2010), there is an increment with respect to the value of obtained with Eq. 1 during the time were the blades are not in front of the column, as can be seen in Fig. 2.

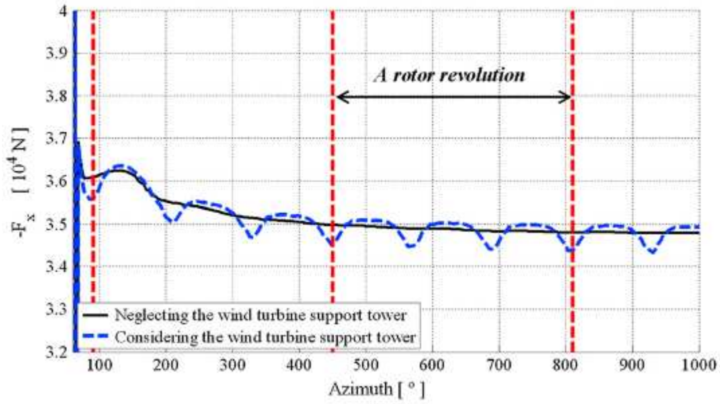

Figure 2: Dynamic evolution of the thrust force generated on the rotating blades subjected to a laminar wind flow, considering the shadow effect of the support structure (Gebhardt et al., 2010).

In this work three models are considered to reproduce the dynamic load on the column: 1) a combination of linear functions, 2) polynomial functions and 3) a standard cosine function. The three cases are illustrated in Fig. 3. The design parameters are: 1. the amplitude A of the oscillation, 2) the duration of the two characteristic stages of the load that are $t1$ (the period on where the load remains approximately constant) and $t2$ (the period where the load decreases and then return to the previous value), and the increment s above the load obtained without considering the column. The period of the variations is known, since it is one third of the period T of the rotating rotor. The combination of linear functions results in the more flexible approach to model all the features observed in Fig. 2. In the polynomial approach, $t1$ and $t2$ can be controlled approximately by changing the order of the polynomial. It results in a smooth curve, but offers less control. Finally, in the cosine function alternative, $t1$ and $t2$ are the same length and the only control parameters are the amplitude A and the increment s.

To the ends of this work, the stages $t1$ and $t2$ will be considered of equal duration, the amplitude A will be 5% of the total load F_B and the increment s will be adopted as the 20% of A. It is worth mentioning that the adoption of fixed values for the parameters aims to achieve a prior understanding of the impact that considering this periodic loading has on the structure. Further studies considering -at least- this parameters as random variables are necessary.

3 STRUCTURE MODEL AND WIND LOAD ON THE COLUMN

The support structure (Figure 4) in this study consists in a 150 m height steel tubular column, with 4.5 m of external diameter and a thickness of 5 cm. A single layer of 4 prestressed guys, symmetrically disposed at 90 degrees from each other in plain view, are anchoraged at 75 m height to the column and 75 m from the and disposed radially at 90 degrees from each other. Each guy have 12.2 cm diameter and are modeled with high resistant wire steel with an elastic modulus of 170 GPa and a ultimate strength (Tu) of 17.5 MN.

An initial tension of 2MN (11.4%Tu) is applied to each guy. The Finite Element Model (FEM) of the column consists in 16 2-node Euler-Bernoulli beam elements with 12 degrees of freedom (DOF), with the addition of second order effect, interpolated with Hermite functions. The guys are modeled with 3-node nonlinear guy elements with 9 DOF, interpolated with quadratic functions.

A 150 m diameter rotor is considered in this study. For the dynamic modeling its effect will

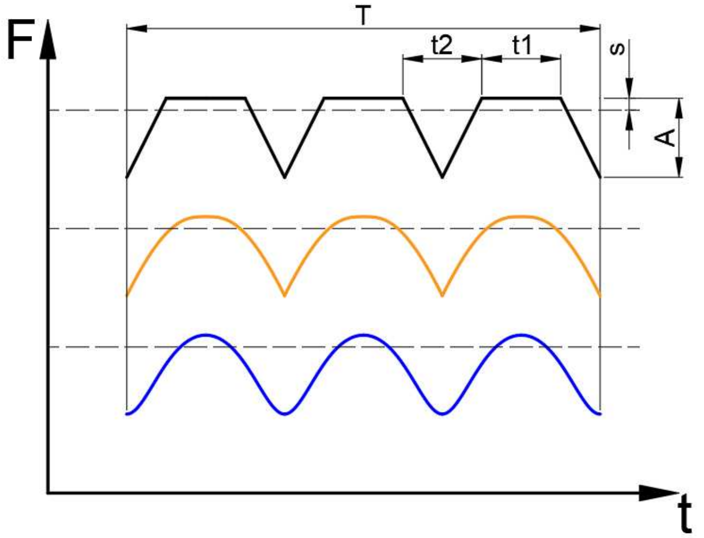

Figure 3: Alternatives to the dynamic model of the loads due the rotating blades considering the presence of the tower: Black=linear composition, Orange=polynomial, Black=sinusoidal function.

be added as a punctual mass of 400 ton (Haldar et al., 2018) at the tip of the column, which include the weight of the total rotor-nacelle assembly.

The wind load acting on the column is modelled as a stochastic process. The mean velocity at a given height is defined using a logarithmic profile:

$$V_m(z) = 2.5u_a \ln(z/z_0) \tag{2}$$

According to Petrini (2009), $u_a = \sqrt{0.006}V_m(z = 10m)$. Fixing $V_m(z = 150m)$ =12m/s in Eq. 2, results in u_a =0.5. Then, the wind load at a given height will be:

$$F_w(z) = 0.61C_sAV_m(z)U(z,t), \tag{3}$$

were $C_s = 0.5$ is the shape factor, A is the projected area perpendicular to the wind direction and $U(z,t)$ is the stochastic time variation of the wind. The load stochastic time variation $U(z,t)$ is reproduced by means of the Spectral Representation Method (SRM) (Shinozuka and Jan, 1972), which consider both time and spatial correlations.

4 DYNAMIC MODEL AND RESULTS

The dynamic response studied in this work is the time series of the displacements at the tip of the column (position of the turbine). To obtain the dynamic response, an optimized finite element model is constructed and the non-lineal time dependent solution is obtained combining a Newmark approach for the integration in time domain, with a fixed time-step of 1/60s and the Newton-Raphson method to solve the non-lineal convergence within each time step. In this work, the parameters t1 and t2 (Section 2 - Fig. 3) are considered equal, the amplitude A = 5%Fb and s = 20%A. The order of the polynomial used in the polynomial model is 2. In Figure 5 the three dynamic load used are depicted along with the static value of the thrust force Fb obtained with Eq. 1.

In Figure 6, the dynamic results of the tip displacements produced by the different load models are depicted. The results are similar in frequency content but vary in shape, amplitude

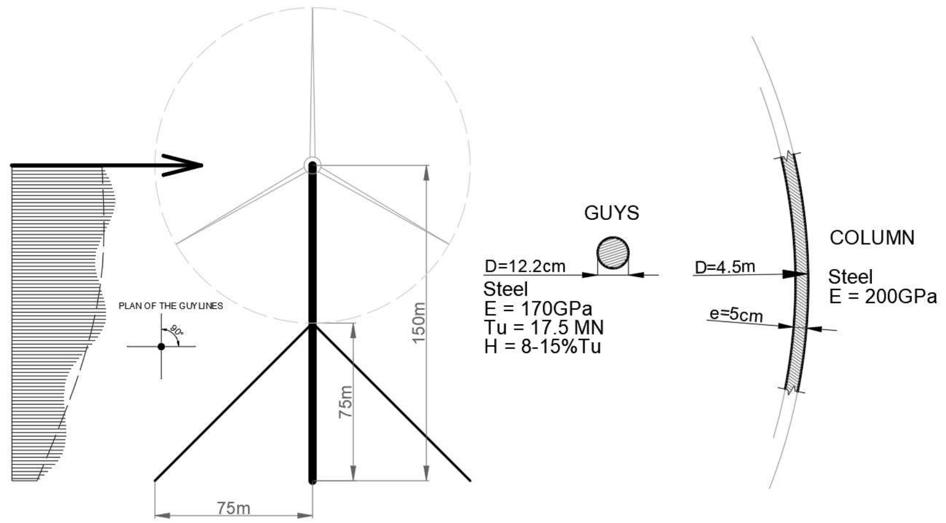

Figure 4: Structure features for the present study.

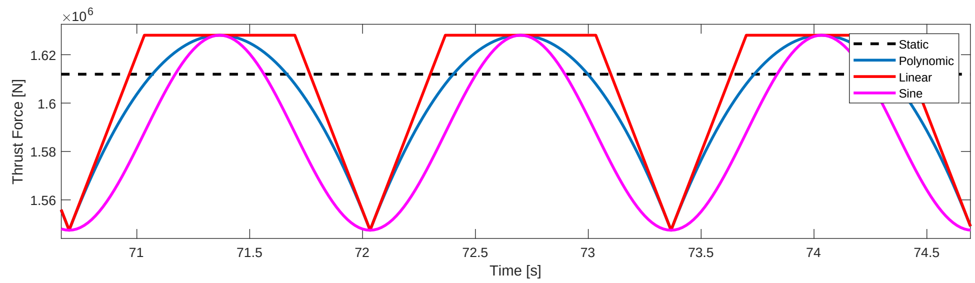

Figure 5: Dynamic thrust -due the interaction of the rotating blades and the flow- load models studied in this work.

and peak values. The highest peaks are observed in the results obtained with the combination of linear functions (curve in orange). Applying the polynomial model (curve in blue) the peak displacements results in lower values than the previous, but share the same shape and frequency content. The main frequency in both cases correspond to the first frequency of the structure, as can be seen in Figures 7 and 8(a). In the case of the sinusoidal model, the results are the lowest both in amplitude and peak value, and the main frequency corresponds to the loading frequency as can be seen in the FFT analysis of the response in Figure 8(b). In the cases of the sinusoidal and polynomial models for the dynamics of the thrust load, the dynamic response is lower than the static response.

5 FINAL COMMENTS

In this work, an exploration on the influence that different models for the dynamic of the thrust load on a wind turbine is presented. The dynamic variation in this load is mainly due the interference effect that presence of the support column produce in the air flow after the blades. Despite this effect is known an reported in the bibliography, there is not a characterization or clear description of its dynamic variation.

Since the structure is nonlinear, is highly sensitive to the dynamic of the load. In the present study, it can be seen that modifying only the shape of the load (using the same amplitude, frequency and peak value), the results can vary widely. Particularly, the results suggests that the

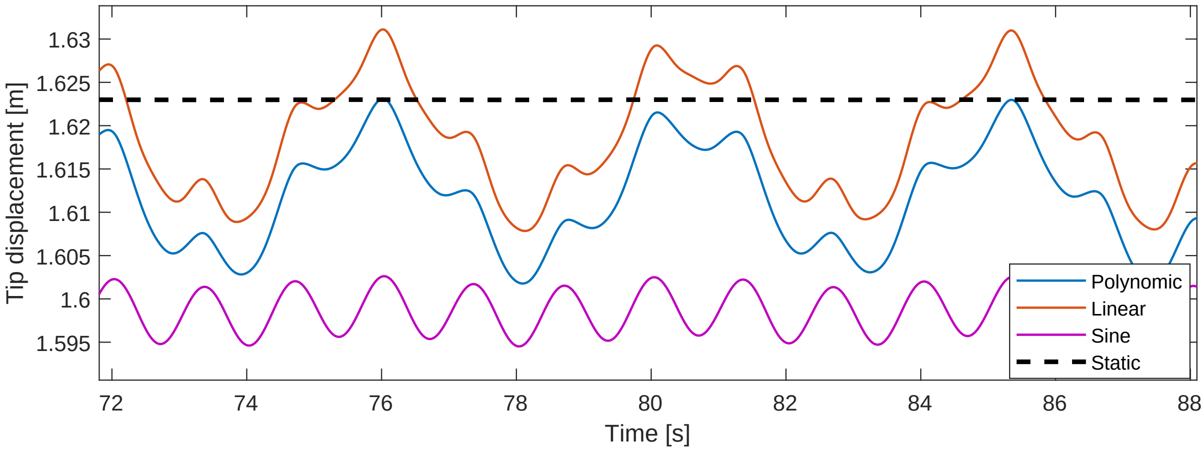

Figure 6: Tip displacements for the different load model alternatives.

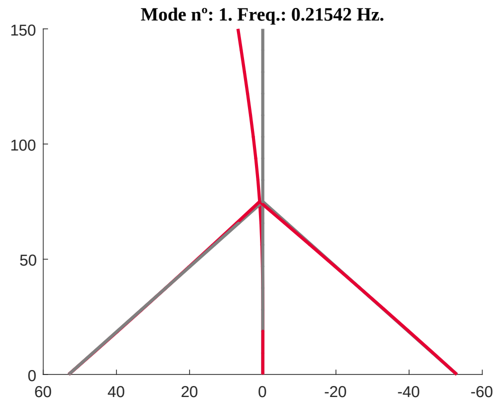

Figure 7: First mode and frequency (0.215 Hz) of the structure.

discontinuities in derivative of the load shape result in higher peak displacements and a stronger influence of the first natural frequency of vibration of the structure in the dynamics of the tip displacements. Then, a detailed description of the dynamic of this loading is required in order to reproduce accurately the dynamic response of the structure.

In this study, the influence of the wind load is marginal. Since the operative wind velocities is relative low, the impact of the stochastic wind loads acting on the column is very small compared with the forces produced by the rotating blades interacting with the wind flow. As future work, the influence of other parameters of the load is necessary. The values used in this study were obtained by observation. Uncertainty propagation studies are the most suitable tool, given the scarce information available. Also, a comparison between results considering the fluid-structure interaction and the present study (on which the effect of such interaction modeled through a the load) will improve the development and characterization of the dynamics of the thrust load.

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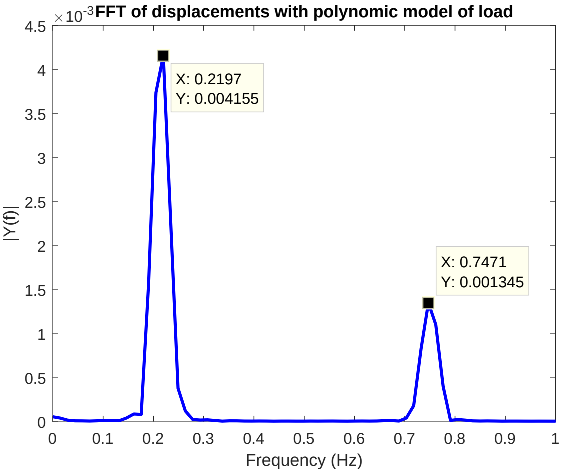
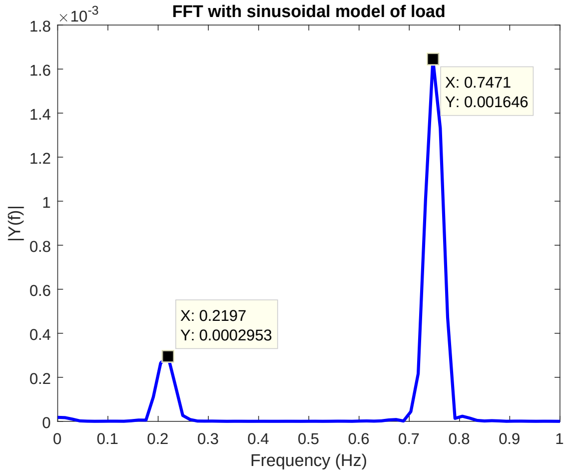


(a) FFT of the tip displacements for the polynomial and linear composition load models.



(b) FFT of the tip displacements for the sine load model.

Figure 8: FFT for the tip displacements for the different load models studied.

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