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State of the art and numerical simulation of high voltage towers against high-intensity winds

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Abstract. High-intensity winds, such as downburst storms, generally do not follow the pattern and characteristics of normal synoptic extreme winds. Therefore, the winds produced by downburst storms must also be taken into account when designing large structures, particularly in Uruguayan territory where they are frequent. In this paper, a bibliographic review of synoptic winds is presented, making comparisons with the Uruguayan wind standard UNIT 50:84 and specific high-intensity winds studies. On the other hand, a numerical simulation of a high-voltage tower loaded by winds from a downburst storm, neglecting the oscillation of the cables. For the simulation, a non-linear dynamic model using Finite Element Method (truss elements) was used. For dynamic analysis, the HHT method provided by the ONSAS software was applied. For the period simulated, the safety factor of the structure was obtained taking into account the creep of the tensile bars and elastic instability. Also it is verified the criteria of AISC 360-16 Standard. Finally, the first five natural frequencies of the structure were found and the first four modes are illustrated. The numerical simulations were carried out with codes developed in MATLAB together with the ONSAS software. They are open and free codes and the link that contains the codes is presented in the article.

Keywords: Downburst storms, High voltage tower, Finite element method, Non-Linear Dynamics

1 Introduction

The problems of mitigating damage from high-intensity winds are obvious and may seem insurmountable. However, it is possible to apply rational and economical solutions on design of large structures to mitigate the damaging effects.

In this work, a bibliographic review of synoptic and non-synoptic winds was carried out, in particular on downburst storms. Also, a numerical simulation of a 220 kV high voltage tower subjected to high-intensity winds was carried out using the Finite Element Method together with non-linear dynamics.

In [1], wind speed curves were studied for the Brazilian territory and a large part of the Uruguayan territory. Then, in [2] the calculation speed, loads on the structure, and the net force on the structure are also studied. Studies on downburst storms such as [2], mention that the force calculations on the tower can be computed as well as the synoptic winds with differences in some coefficients.

The models of the downburst storms are similar to the model of flow called ”wall jet”, obtaining models of wind speed and velocity profiles based on the position, the diameter of the jet and roughness of the terrain [3], [4], and [5]. On the other hand, a study is presented in which the wind speeds of a downburst storm that took place in Germany were measured [6], managing to extract the information of the average wind speed to be used.

Then, the article [7] studies a scale, rigid high-tension tower, tested in a wind tunnel in which drag coefficients are calculated for different heights and different angles of attack. Drag coefficient values were also studied, taken from the [8] norm, comparing them with that presented in [7].

Turning to the computational model, a numerical simulation of the high-voltage tower subjected to stresses from a downburst storm was carried out. The simulation was carried out from codes developed in the MATLAB software together with the ONSAS software, using truss nonlinear dynamic analysis. The forces on the tower were found as presented in the article [2] and the speed of the storm was extracted from the images presented in [6]. On this article, the safety factor of the structure was found for every instant of time. For the safety factor, the tensile creep and elastic instability were taken into account for the compression elements, considering the provisions of the AISC 360-16 Standard.

Finally, the tower's natural frequencies and modes of vibration were calculated, being all-natural frequencies greater than 1 Hz. The first five natural frequencies are presented with images of the first four associated modes.

2 Bibliographic review

This section presents the books, standards, and scientific articles that deal with the topic of high-voltage towers in extreme winds.

In the article [1] the basic graphs of wind speeds for the entire Brazilian territory and its surroundings are constructed, covering a large part of the Uruguayan territory. For the interest of this work, wind curves are shown for a large part of the Uruguayan territory.

On the other hand, the Uruguayan wind standard UNIT 50:84 defines the criteria presented in eq (1). Referring to coast as Río Uruguay, Río de la Plata, or Atlantic Coast.

$$\begin{cases} v = 43.9\ m/s & \text{less than 25 } km \text{ from the coast.} \\ v = 37.5\ m/s & \text{more than 25 } km \text{ from the coast.} \end{cases} \tag{1}$$

Comparing the mean wind speeds between UNIT 50:84 with the article [1], two observations were made. First, for locations near the coast, the norm is more conservative since it takes 43.9 m/s and the article shows that the maximum occurs near to the Uruguay River and it is 42 m/s. However, for locations within the Uruguayan territory, the article presents wind speed curves that range from 34 m/s to 40 m/s, being the least conservative standard in this case.

Continuing with wind reserches, in the technical article [2], guidelines are provided on the design of transmission lines to mitigate the damage produced by high-intensity winds (wind speed greater than 45 m/s). As in the Uruguayan wind standard, this article considers that the calculation speed is found from the basic regional wind velocity V_{design} affected by factors that modify it depending on the specific place where it is finding the structure. The eq (2) shows how to find the calculation speed V_z.

$$V_z = V_{design} M_d M_{z,cat} M_s M_t. \tag{2}$$

Where V_{design} is the basic regional wind velocity (2-3 second gust), then M_d is considered when there are nearby constructions, $M_{z,cat}$ is the gusting wind speed multiplier for the terrain category at a given height, M_s is defined as the wind direction multiplier and M_t is the topographic coefficient.

The dynamic calculation pressure q_z on the structure is found as expressed in eq (3), using the velocity V_z in m/s, the result is expressed in kPa.

$$q_z = 0.5 \rho_{air} V_z^2 \times 10^{-3}. \tag{3}$$

Being ρ_{air} the density of the air. The eq (3) is similar to that expressed in UNIT 50:84: $q_z = V_z^2/1630$ (result expressed in kN/m^2).

For lattice towers that are essentially square or rectangular in plan, the force in the direction of the wind throughout the tower section can be calculated as shown in the eq (4), the result is expressed in kN.

$$F = q_z C_d A. \tag{4}$$

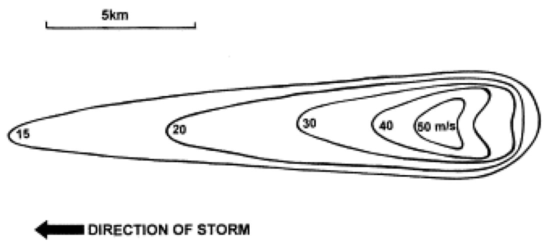
Where A is the solid projected area of a face of the section of the structure in a vertical plane along the face and C_d is the Drag coefficient of the structure.

Turning to the study of downburst storms, this article, [2], emphasizes that the pressures generated by downburst storms can be calculated as the pressures coming from synoptic winds, except for the modification of the M_z factor and the design speed.

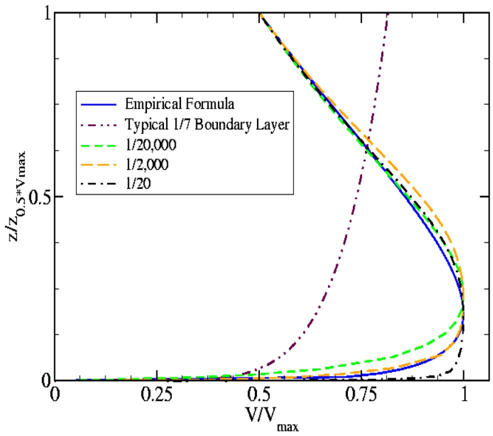
Generally, 220 kV high-voltage towers are in the range where $M_{z,cat}$ is equal to 1. Therefore, the application of reduced values of $M_{z,cat}$ for downburst storms will be limited to tall tower applications, greater than 55 m.The following recommendations are based on the standard [8] and researches by [4] and [9].

Refered to downburst storm models, the analyzes performed in the article [3] show that the flow for the radial and vertical profiles of the wind speed in a downburst storm is similar to the flow model called "wall jet". In [4], the flow field is compared to a jet of fluid striking a flat, rigid surface. The important characteristics observed are the rapid fluctuations in the wind directions and the influence of the roughness of the terrain. The article presents a simplified empirical model of a downburst storm that shows the variation of the magnitude of the radial component of the mean wind speed. The variation is linear up to a point of maximum velocity (V_{rmax} at position r_{max}) and then decreases exponentially. In turn, to the radial wind speed, the translation speed of the center of the downdraft is added to give the resulting wind speed as shown in Figure 1a.

On the other hand, the study of wind speed as a function of height is presented. It was found that, in opposition to the boundary layer wind profile, the maximum speed in downburst storms occurs at relatively low altitudes. Figure 1b shows the velocity profiles as a function of height for the following cases: The empirical formula developed by [10]; The boundary layer wind formula for synoptic winds with roughness exponent of the terrain 1/7; Other profiles obtained from computational simulations of [5] with various Reynolds numbers (for different model scales of a real event); and reduced-scale physical simulations in laboratories. The article [6] presents data



(a) Wind speed curves in a convective storm. The image was taken from the article [4].



(b) Profile of average wind speeds normalized as a function of height. The image was taken from the article[5].

Figure 1. Average speed profiles for winds produced by a downburst storm.

on a downburst storm that occurred in Germany. Average wind speed curves and their fluctuating component as a function of time, Figure 2, are presented. They also present the graph of the power spectral density as a function of the frequency for the measured storm, showing how the range of maximum powers is given for frequencies less than 1 Hz and then decays exponentially as the frequency increases.

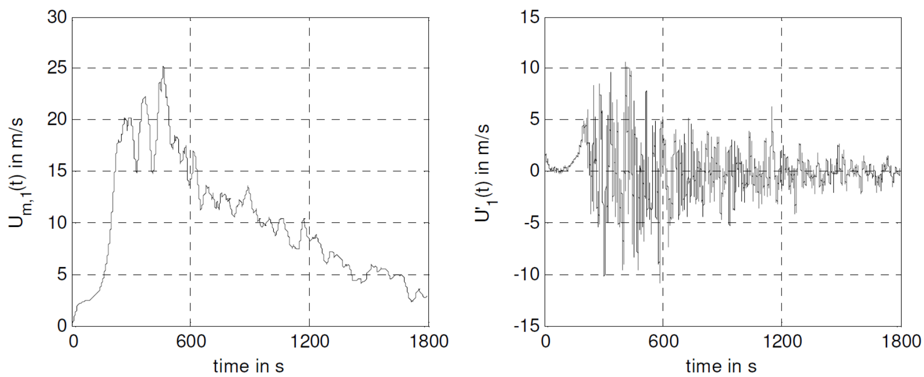


Figure 2. Average wind speed and its fluctuating component of a downburst storm as a function of time. Images were taken from the article: [6]

Turning to the study of the Drag coefficient, in [8] a table with coefficient values is presented. The coefficient values are expressed as a function of the angle of attack of the wind and the ratio of the solid projected area to the enclosed projected area. In [7] the tower model used in the experimental test, the finite element model, wind profiles, and Drag coefficients used are shown. When comparing the Drag coefficient with [2], there is a great similarity for medium and high heights. On the other hand, for low heights, the Drag coefficient differs considerably.

3 Problem formulation

This section presents the problem to be addressed. Using finite elements together with non-linear dynamics, a simulation of a high-voltage tower was carried out under the winds produced by a downburst storm.

The codes to achieve the simulation were developed in the MATLAB software, used in combination with the ONSAS software. All the codes used are published in the following link: Codes[1].

These codes allow a non-linear dynamic simulation for lattice structures. In the Finite Element analysis, truss elements were considered implementing rotated engineering deformation and geometric nonlinearity. The consistent mass matrix was used as the mass matrix and it was considered a structure without damping. Then, as a numerical integration method over time, the HHT method provided by the ONSAS software was used with parameter $\alpha = -0.05$ and time step 1 s. The HHT method has the particularity of being unconditionally stable on the time step.

It was considered a 220 kV high voltage tower made up of angular bars, the tower model is based on the articles [11] and [12]. For a better understanding of the tower, it is recommended to see Figure 4, where images of the undeformed tower are presented together with its associated modes.

Going deeper into the analysis, to find the force generated on the structure, the eq (2) was used, considering all coefficients equal to 1. The basic regional wind velocity used was the wind speed shown in Figure 2 with an increase of 5 m/s to contemplate the fluctuating component of the wind speed.

Figure 1b shows the profile of speeds that impact on the studied tower when a downburst storm occurs. When viewing the velocity profile in the range of the tower height, the approximation of a constant wind profile with magnitude the maximum speed of the storm is considered appropriate. Choosing a constant speed profile equal to the maximum speed of the profile is on the conservative side.

The pressure on the structure was calculated from eq (3). Then the force applied on the structure was found from eq (4) considering $C_d = 3.4$ since the ratio of the solid projected area to the total enclosed area, calculated from the commercial software *Inventor Professional*, is $\delta = 0.11$ with wind attack angle 0º. The force exerted by the wind was distributed in all the nodes except in the four fixed nodes (foundations of the tower). Furthermore, the mass forces on the tower were added as constant forces over time.

As a result, the safety factor was calculated as a function of time for the simulated tower. In this way, we have an estimate of the mechanical behavior of the tower in the face of a downburst storm such as the one studied. It is shown how no elements reach creep or present local elastic instability considering the failure criteria stipulated by the AISC 360-16 Standard. Besides, the natural frequencies and modes of vibration of the tower were found.

4 Numerical analysis and results

This section presents the results from the numerical analysis performed using the Finite Element Method and nonlinear dynamics.

As a result, the safety factor of the tower was obtained as a function of time as shown in Figure 3. When studying the safety factor of the structure and this being greater than one for the entire time interval in which the storm was simulated, it indicates that no element has entered yield or has reached the critical buckling stress. In these circumstances, the tower can withstand the stresses from a convective storm with the characteristics used. The minimum factor of safety experienced by the tower is $SF = 1.74$ in an instant close to the peak of the highest speed of the storm.

Regarding the natural frequencies and modes of the structure, in Figure 4 the first four modes of the structure are shown with their respective natural frequencies. As shown, all frequencies are greater than 1 Hz. This leads to good results since when studying the density of the power spectrum, for frequencies greater than 1 Hz, the associated power is minimal and continues to decline as the frequency increases.

It is also worth highlighting the fifth of the tower's natural frequencies, this being $\omega_i = 7.11\ Hz$ and its associated mode is torsion, unlike the previous modes.

[1]Link: https://drive.google.com/drive/folders/12dvIgGceZBLIVtpej4p0v-v6pylkPDyC?usp=sharing

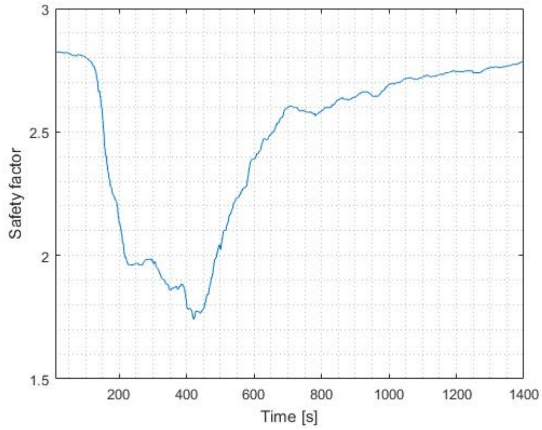
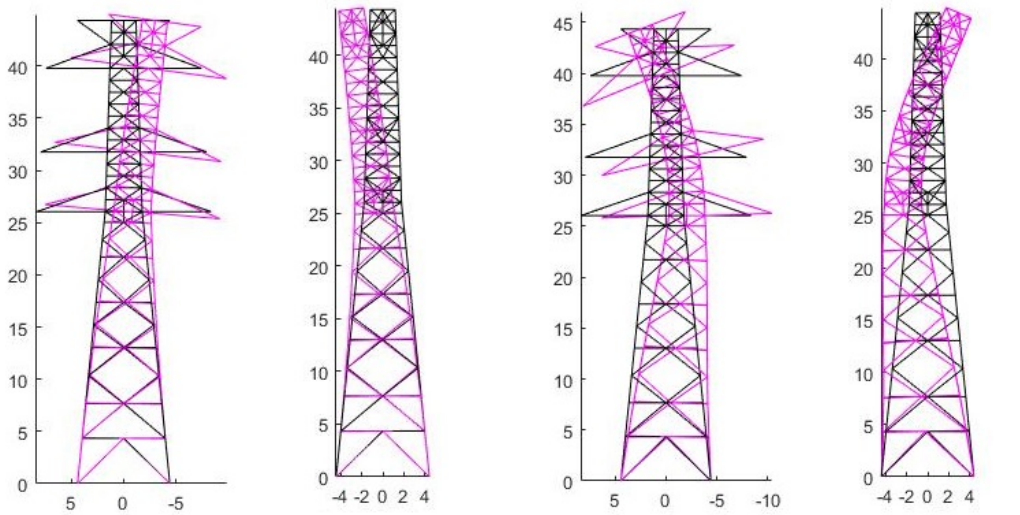


Figure 3. Factor de seguridad de la estructura en función del tiempo.



(a) 1^{st} mode. $\omega_1 = 2.01\ Hz$

(b) 2^{nd} mode. $\omega_2 = 2.03\ Hz$

(c) 3^{th} mode. $\omega_3 = 6.60\ Hz$

(d) 4^{th} mode. $\omega_4 = 6.84\ Hz$

Figure 4. First four modes and natural frequencies of the structure.

5 Conclusions and future work

This article presents a bibliographic review of the fluid structure interaction, in particular winds from downburst storms.

Then, a study of the calculation of the forces on truss structures, in particular high-tension towers, against synoptic and non-synoptic winds is presented. Besides, a comparison of the calculation was made concerning the Uruguayan wind standard UNIT 50:84.

Regarding downburst storms, a bibliographic review about the velocity profiles and Drag coefficients is shown from numerical and experimental tests. Besides, wind speed data for a downburst storm that occurred in Germany is presented.

When carrying out the numerical experiment of a 220 kV high-tension tower loaded by a downburst storm, it was found that the tower is capable of withstanding an event of these characteristics. When studying the safety factor as a function of time, it is found that it is greater than 1 in the entire time interval in which the storm occurs, with the minimum value of $SF = 1.74$ for an instant close to the highest speed peak from the storm.

Analyzing the natural frequencies of the structure, the frequencies are all greater than 1 Hz. These results are to be expected for structures of this type, the minimum frequency must be higher then 1 Hz. Frequencies far removed from the frequencies of the wind prevent the structure from entering into resonance. In the article

[6] it is shown that for frequencies greater than 1 Hz the density of the power spectrum is minimal and decays exponentially with increasing frequency. Finally, the codes developed in this work are open and are published in the article.

As future work, it is proposed to continue investigating downburst storms, their interaction with steel structures, and their numerical modeling. By having the tower model, some software can be used to simulate the interaction of the fluid with the rigid tower and find more reliable Drag coefficients. In this work, the total force that the wind exerts on the tower was calculated, so codes could be developed that calculates the force on different panels of the tower or even on each one of the bars and distribute the force in the nodes, achieving greater precision.

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References

[1] Beck, A. T. & Corrêa, M. R., 2013. New design chart for basic wind speeds in brazil. *Latin American Journal of Solids and Structures*, vol. 10, n. 4, pp. 707–723.
[2] CIGR, E., 2012. Overhead line design guidelines for mitigation of severe wind storm damage. *Technical Brochure*, vol. 485.
[3] McClure, G., Langlois, S., & Rogier, J., 2008. Understanding how overhead lines respond to localized high intensity wind storms. pp. 1–10.
[4] Holmes, J. D. & Oliver, S., 2000. An empirical model of a downburst. *Engineering structures*, vol. 22, n. 9, pp. 1167–1172.
[5] Hangan, H. & Freure, P., 2002. *Numerical Simulations of High Intensity Winds: Downburst Simulations*. Institute for Catastrophic Loss Reduction.
[6] Stengel, D. & Thiele, K., 2017. Measurements of downburst wind loading acting on an overhead transmission line in northern germany. *Procedia engineering*, vol. 199, pp. 3152–3157.
[7] Zhang, W., Zhu, J., Liu, H., & Niu, H., 2015. Probabilistic capacity assessment of lattice transmission towers under strong wind. *Frontiers in Built Environment*, vol. 1, pp. 20.
[8] AS/NZS7000:2010, 2010. Overhead line design – detailed procedures.
[9] Holmes, J. D., Hangan, H., Schroeder, J., Letchford, C. W., & Orwig, K. D., 2002. A forensic study of the lubbock-reese downdraft of 2002. *Wind and Structures*, vol. 11, n. 9, pp. 137–152.
[10] Wood, G. S., Kwok, K. C., Motteram, N. A., & Fletcher, D. F., 2001. Physical and numerical modelling of thunderstorm downbursts. *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 89, n. 6, pp. 535–552.
[11] Visweswara Rao, G., 1995. Optimum designs for transmission line towers. *Computers & structures*, vol. 57, n. 1, pp. 81–92.
[12] Tort, C., Şahin, S., & Hasançebi, O., 2017. Optimum design of steel lattice transmission line towers using simulated annealing and pls-tower. *Computers & Structures*, vol. 179, pp. 75–94.