Numerical analysis of vibrations of cable and tower of electric power transmission lines

Farias, J.Y.[1], Silva, R.S.Y.R.C.[2], Miranda, A.C.O.[3], Guimarães, M.[4]

[1,2,3]*Department of Civil Engineering, Brasilia University*
Campus Darcy Ribeiro, 70.91-900, DF, Brazil
jonasyamashita1@gmail.com; ramon.silva2@unb.br; amirandaspac3e@gmail.com; marlos.jrg4@gmail.com
[4]*Eletrobrás Furnas, Goiânia, Goiás, Brazil*

Abstract. This article presents preliminary results on the behavior of towers and cables in power transmission lines using a three-dimensional numerical model. Computational analyses were performed considering the plastic behavior of ASTM-A36 and ASTM-A242 steels used in the tower. The mechanical model included rigid connections and fixings, and four vibration modes of the metal tower were obtained: transverse, longitudinal, torsional, and flexural. To validate the dynamic behavior of the cable, the classical problem of the violin string was used, verifying that natural frequencies increased with cable tension. Receptance analysis allowed obtaining displacement curves as a function of wind excitation frequency for different orientations. Critical wind excitation frequencies were related to the vibration modes of the structure. The geometry and dynamic behavior of the transmission tower and cable were explored, providing information on vibration frequencies and dynamic response of the structure under different wind orientations. Four vibration modes were found: transverse, longitudinal, torsional, and beam bending.

Key words: Vibration, Tower, Cable, Electric Transmission Lines

1- Introduction

Brazil faces increasingly frequent and intense storms, causing severe impacts on the electrical sector. Windstorms knock down transmission towers, landslides destroy distribution lines, and heavy rains and lightning cause power outages. To meet the growing demand for energy, transmission towers are being constructed taller with complex geometries and greater distances between them. The energy transmitted through these systems concentrates at low frequencies, and the structural frequency decreases as the height and span of the transmission lines increase. This requires transmission line projects to carefully consider the dynamic wind loading and its impact on the structural response. The collapse of these transmission tower-cables under wind loads has resulted in power grid disruptions over large areas, causing serious consequences for the population and significant financial losses.

Compared to other natural disasters, wind hazards have a broader impact and are the primary cause of damage to power transmission lines in Brazil, especially considering its location with minimal tectonic activity. Reports of transmission tower collapses have been observed in different parts of the world. Numerical and experimental studies have been conducted to better understand the behavior of these structures under wind loads, but there is a need for further research focused on the collapse of the tower-cable system.

Transmission towers have complex structural geometries and exhibit nonlinear vibration due to the flexibility of the transmission cables. The interaction between tower movement and cable oscillation makes the dynamic behavior quite complex. Therefore, it is crucial to consider the behavior of both cables and towers for a more accurate and efficient analysis of power transmission lines. Ideally, the tower-cable system should be treated as a whole during the modeling and analysis of these structures, but initially, they will be treated separately. Thus, the objective of this paper is the development of a three-dimensional dynamic model of a tower in power transmission lines, aiming to understand the dynamic behavior of the structure, with emphasis on its vibration modes.

2 - Literature Review

In this section, a preliminary literature review is presented, covering the main topics relevant to this research, including theoretical and numerical analysis of vibration frequencies, wind loads. Transmission lines (TLs) are large-scale structures that play a crucial role in transporting electrical energy from generating stations to substations and, consequently, to consumers (McClure and Lapointe [1]) . These lines consist of various elements, such as towers, conductive cables, insulators, lightning conductors, and foundations, and in certain cases, they may also include dampers, spacers, and markers for multiple conductors (McClure and Lapointe [1]).

The design of transmission towers depends on various factors, such as the number of circuits, conductor arrangement, adopted shape, electrical voltage, and the specific function of the tower in the line (Brazeiro [2]). There are three main types of towers used in TLs: terminal towers located at the beginning and end of the line, anchoring towers employed at intermediate points to provide greater system rigidity, and suspension towers responsible for supporting the line cables (Brazeiro [2]).

Terminal towers are designed to be robust and capable of withstanding all normal and exceptional loads that may act upon them. Anchoring towers play the role of tension points and are crucial in preventing cascading effects in the line. On the other hand, suspension towers are the most common throughout TLs and, therefore, hold significant financial importance, demanding efficiency and cost-effectiveness in their design (Brazeiro [2]). In summary, transmission lines have an essential function in the safe and efficient transportation of electrical energy, comprising various elements such as towers and cables, designed to meet the requirements of each section of the line (McClure and Lapointe [1]). Proper tower design, considering the specific factors of each case, is fundamental for the smooth operation of the transmission system (Brazeiro[2]).

2.1 - Analytical Models for Vibration Frequencies

To examine the structural response of a transmission cable and tower system, several analytical models have been developed and presented (Irvine [3]; Kempner Jr. and Smith [4]; Ozono and Maeda [5]). The analytical solution is provided by Thomson in 1965, who presented the general solution to the differential equation associated with the problem of free vibration of a linear mass rope with length (L), linear mass density (ρ) and tensioned by a force (T). The equation is described through the free body equilibrium of a cable segment and takes the form:

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 y}{\partial t^2} \tag{1}$$

where $c = \sqrt{T/\rho}$ is the wave propagation velocity in the cable. The solution of the differential equation (1) is obtained through separation of variables. In this way, the natural frequencies of the structure are given by:

$$f = \frac{n}{2L}c = \frac{n}{2\mathrm{L}}\sqrt{\frac{T}{\rho}} \qquad \mathrm{n}=1,2,3.... \tag{2}$$

Li et al.[19] conducted studies on the dynamic behavior of the coupled tower-cable system, developing two simplified two-dimensional analytical models based on planar trusses to represent vibrations within and outside the plane of the transmission line. The masses, stiffnesses, and damping of the truss members were concentrated at the nodes of the models, and various types of extreme wind loads were considered. Despite considering some degree of coupling, it is still a rather limited model, necessitating the use of numerical methods for more realistic studies.

2.2- Numerical Studies on Collapse in Power Transmission Tower Lines

Conventional design standards for power transmission tower-cable systems do not account for the dynamic interaction between towers and cables, merely assuming elastic behavior under dynamic excitations (Lee and McClure [6]). However, to predict failures caused by shear due to tornadoes, for example, numerical methods like the Finite Element Method (Savory et al. [7]) are necessary. Several studies have utilized techniques such as instantaneous element removal to investigate the progressive collapse of transmission towers (Asgarian et al.[8]). Moreover, analyses based on the concept of critical collapse curve fragility have been applied to assess the collapse of towers under wind and rain loads (Fu et al.[9]).

In addition to conventional design based on structural flexibility to dissipate vibrational energy, research has focused on control devices to prevent catastrophic damages in transmission line systems (Chen et al.[10]). Among the control devices, energy dissipation dampers have been prominent, including magnetorheological, friction, tuned mass, and passive tuned mass dampers (Li Tian et al.[11]). Studies have demonstrated the effectiveness of these dampers in controlling dynamic responses of structures, particularly in wind loading scenarios (Chen et al.[12]; Kilroe [13]). Computational models have also been employed to analyze vibration control, such as the study of "galloping" mode in transmission tower structures.

2.3 - Consideration of Wind Load

Transient loads generated by winds are the primary external forces acting on electricity transmission tower structures. Generally, the design wind loads are determined through field measurements, wind tunnel tests, or numerical simulations. However, studies that consider experiments at reduced or full scale, or field measurements on instrumented towers, are quite limited compared to theoretical and numerical investigations of the tower-transmission line system performance.

Researchers, such as Tomokiyo et al.[14], reported on the analysis of damages caused by typhoons on transmission towers in mountainous regions of Japan. Deng et al.[15] conducted a wind tunnel study on wind-induced vibrational responses in an ultra-high voltage (UHV) tower-cable transmission system, using a discrete stiffness method in the aeroelastic model. Additionally, Liew and Norville [16] presented a method to study the response of a transmission tower structural system subjected to wind loads, considering wind velocities and conductor loads. Yasui et al.[17] described an analytical method to analyze wind-induced vibrations in power transmission towers coupled with power lines, discussing the influence of differences in transmission support systems and peak factors. Finally, Battista et al.[18] proposed a novel analytical-numerical modeling approach to assess the stability of transmission line towers under wind action during design.

3 - Methodology

Using program ABAQUS, a three-dimensional numerical model of the tower-cable transmission system was developed, allowing for the analysis of wind orientations and structural vibration modes. The decision to model individual tower members instead of concentrating their properties at the structure's nodes enables an analysis of progressive collapse, including element deletion and simulation of widespread damage. Thus, the methodology consists of the following steps: a) adapting the geometry of the tower under study obtained from CAD project drawings to 3D CAE; b) defining the constitutive model, physical parameters, element types, and analyses; c) constructing a numerical model for the tower and transmission cable.

In this study, the goal is to replicate the geometry of a distribution tower structure using ABAQUS/CAE, considering the connections between members, boundary conditions, and material types. An analysis of the structure's vibration modes is conducted, followed by a receptance analysis, aiming to relate the structure's displacements to a unit load over a frequency excitation spectrum, comparing the results with the previous modal analysis. The unit loads are applied in different directions, simulating the angle of incidence of the winds (longitudinal, transverse, and at 45º).

4 - Results

The preliminary results of this research are presented, including the adaptation of the tower and transmission cable geometry. The three-dimensional geometric model of the structure was constructed, considering the profiles of the elements according to the provided drawings. Some photos of the real structure were used for the three-dimensional adaptation.

Computational analyses of the structure's behavior were carried out based on the model, using ABAQUS software and considering the plastic behavior of ASTM-A36 and ASTM-A242 steels used in the tower. The mechanical model adopted for the metal lattice towers is typically simple, with truss and/or spatial portal elements, immovable links, and rigid or pinned connections. The choice of connection type was based on the drawings and the type of connection used. For this study, connections with two bolts were treated as rigid connections, while simple connections were treated as pinned. The model consists of a total of 1124 elements, and geometrically non-linear analyses were performed.

Before conducting the tower vibration analysis, the cable simulation was validated by comparing the vibration frequency of the cables with the expected response based on the classical "violin string" problem, described below.

4.1 - Classical Violin String Problem

To validate the dynamic behavior of the tensioned cable, a numerical model was created with the dimensions and clearances of the transmission lines' design. The validation is performed using the classical violin string problem, which studies the vibration of a linear element tensioned by a force (T), and its analytical solution will be compared with the model's results. For the extraction of the cable's vibration modes, two analyses were performed: a static analysis of cable tensioning and an extraction of vibration modes from the model with stress states at the end of the loading stage. In ABAQUS, geometric nonlinearity is considered through the NLGEOM solver, which allows for the extraction of vibration modes from a previous state of tension obtained from the tensioning stage.

For both the numerical and analytical models, the following parameters were used: cable radius $r = 0.01$ m, Young modulus $E = 210$ GPa, density $\rho = 7850$ kg/m³, cable length (L) = 50 m, and the cable tension value (T) varied between 500 N and 2000 N. The analytical solution was obtained from equation (8), and the results are shown in Table 1.

Table 1. Analytical and numerical solutions for the cable frequency problem.

Force T (N)	Analytical frequency (Hz)	Numerical frequency (Hz)	Error (%)	Force T (N)	Analytical frequency (Hz)	Numerical frequency (Hz)	Error (%)
500	f_1=0.0714	0.0715	0.06	1500	f_1=0.1237	0.1236	0.05
	f_2=0.1428	0.1432	0.23		f_2=0.2474	0.2469	0.20
	f_3=0.2143	0.2154	0.53		f_3=0.3711	0.3695	0.44
	f_4=0.2857	0.2884	0.95		f_4=0.4948	0.4910	0.76
1000	f_1=0.1010	0.1010	0.02	2000	f_1=0.1428	0.1427	0.07
	f_2=0.2020	0.2018	0.09		f_2=0.2857	0.2850	0.25
	f_3=0.3030	0.3024	0.19		f_3=0.4285	0.4261	0.56
	f_4=0.4040	0.4027	0.33		f_4=0.5713	0.5657	0.98

It is possible to validate the numerical data based on analytical results with errors lower than 1%. Thus, the model is considered calibrated and ready for coupling.

In Figure 1, the correlation of the first vibration frequencies for various applied force values is presented. It can be observed that as the cable tension increases, the natural frequencies also increase.

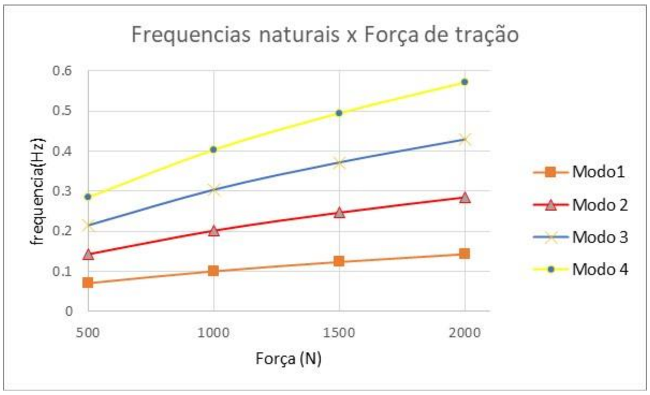


Figure 1 - Vibration Frequency

4.2 Modes of Vibration of the Metal Tower

After adapting the geometry, introducing the profiles used, and specifying the density and elastic properties of the steels used in the structure, global stiffness and mass matrices are obtained. From these tensors, the eigenvalue problem is solved, and the associated modes and vibration frequencies are obtained (Figures 2, 3, 4, and 5).

The first mode obtained was the transverse vibration mode of the structure (f_1=7.98 Hz), followed by the longitudinal vibration mode (f_2=10.653 Hz), then the torsional mode of the structure (f_3=16.356 Hz), and finally the bending mode of the beam (f_4=31.359 Hz). Due to the low wind excitation frequencies, it can be said that the structure is more dynamically susceptible to winds in the transverse direction. Mode 4 is a mode of a specific member of the structure (beam simply supported on the deltas), and changes in this component will have a direct impact on this vibration frequency.

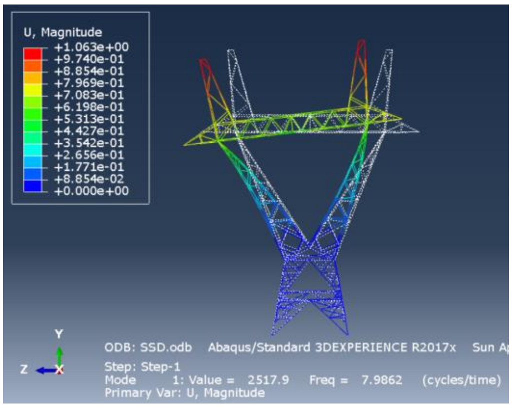


Figure 2 - Mode 1, Transverse Vibration

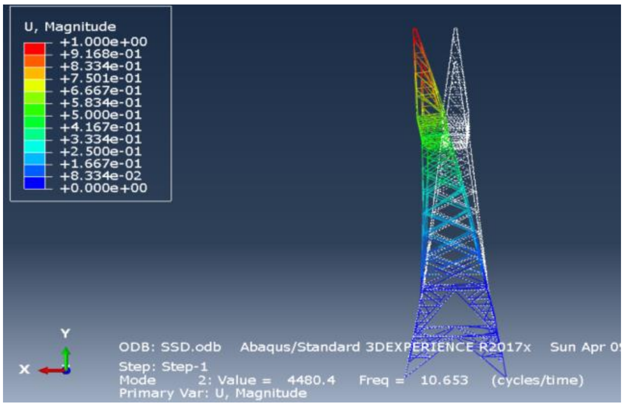


Figure 3 - Mode 2, Longitudinal Vibration

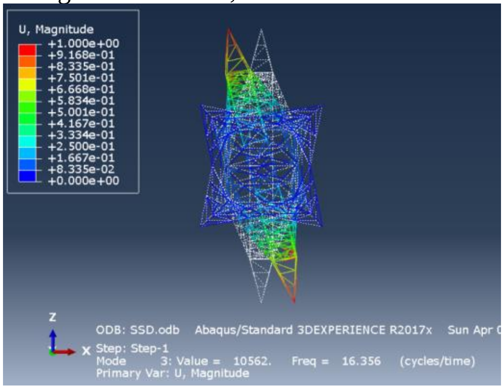


Figure 4 - Mode 3, Torsional Vibration

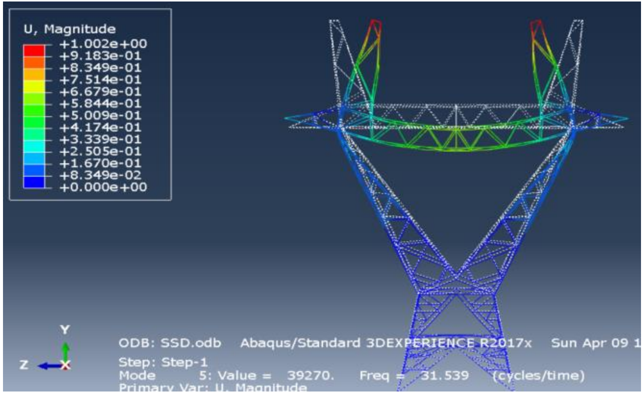
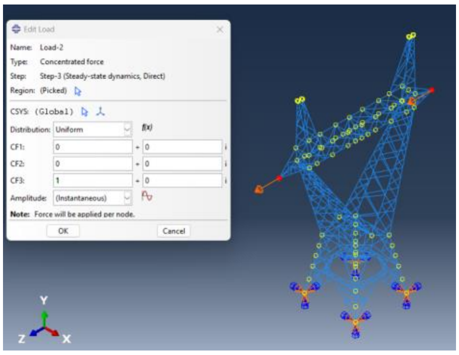


Figure 5 - Mode 4, Beam Bending Vibration

4.3 - Receptance Curves

This type of analysis (steady-state dynamics) allows obtaining displacement curves as a function of the excitation frequency of a unit load acting on the structure. This type of loading does not consider the distribution of the pressure profile generated by wind velocity, but it provides an understanding of the dynamic response susceptibility of the structure for a certain wind orientation. The unit load was applied at the coupling point with the conductors, simulating a force driven by cable vibration (Figure 6).

Due to the symmetry of the structure along its axes, winds in the transverse, longitudinal, and 45° directions with respect to these axes were simulated. For winds in the transverse direction (Figure 7), it is possible to observe that the most critical frequency is precisely around 8 Hz (first vibration mode). This occurs because the wind acting in this direction primarily excites the transverse displacement mode presented by the first mode. In the longitudinal direction (Figure 9), a behavior analogous to the transverse wind can be verified, but this time the excited frequency is that of mode 2 (f_2=10.653 Hz). For winds acting at 45° (Figure 8) parallel to the ground, or at any angle between 0° and 90°, it is observed that both vibration modes 1 and 2 were excited, and the total movement of the structure would be a modal superposition of these. The modes will be more excited depending on the wind components in the longitudinal and transverse directions (wind orientation) and excitation frequency. It is expected that, for frequencies between 8 and 10.653 Hz, the structure will vibrate in both axes, creating an "eight" trajectory when viewed in plan view.


Edit Load

Name: Load-2

Type: Concentrated force

Step: Step-3 (Steady-state dynamics, Direct)

Region: (Picked)

CSYS: (Global)

Distribution: Uniform

CF1: 0 + 0 i

CF2: 0 + 0 i

CF3: 1 + 0 i

Amplitude: (Instantaneous)

Note: Force will be applied per node.

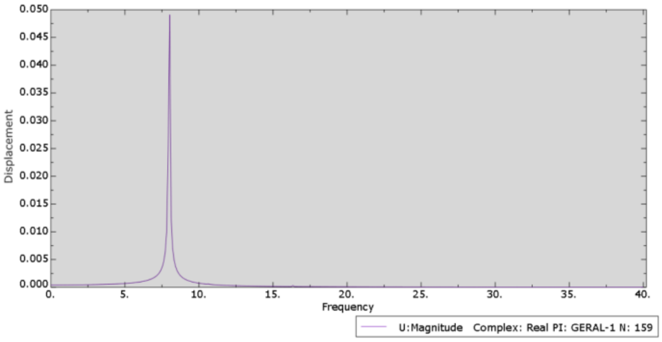
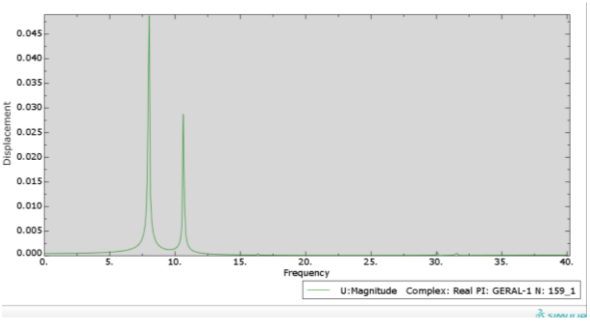


Figure 6 - Applied Unit Load

Figure 7 - Receptance Curve for Transverse Winds



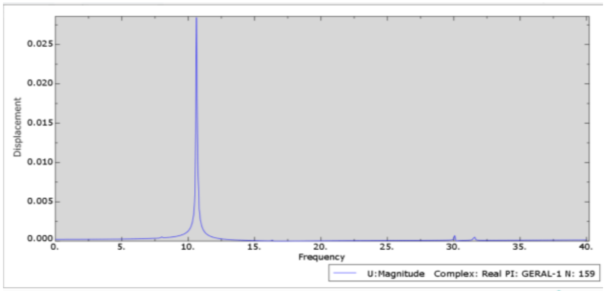


Figure 8 - Receptance Curve for 45° Winds

Figure 9 - Receptance Curve for Longitudinal Winds

5 - Conclusions

Computational analyses of the structural behavior were performed based on a three-dimensional model of the tower, using the ABAQUS software and considering the behavior of ASTM-A36 and ASTM-A242 steels used in the tower. The mechanical model adopted for the lattice metal towers included connections with two bolts treated as rigid links and simple connections treated as fixed supports. The tower model consisted of a total of 1124 B21-type elements. The choice of the type of connection was based on the design plans and the type of connection used.

To validate the dynamic behavior of the tensioned cable, a numerical model was created with the dimensions and clearance of the transmission lines' design. The classical violin string problem was used to study the vibration of a tensioned linear element. The natural frequencies increased as the cable tension increased, and the results were validated through comparison with the exact analytical solution. The vibration modes of the metal tower were obtained after adapting the geometry and specifying the material properties. Four vibration modes were found: transverse, longitudinal, torsional, and beam bending.

The receptance analysis allowed obtaining displacement curves as a function of the excitation frequency for different wind orientations (transverse, longitudinal, and 45°). The critical wind excitation frequencies were related to the structure's vibration modes. The research explored the adaptation of geometry and dynamic behavior of the tower and transmission cable, providing valuable information about vibration frequencies and the dynamic response of the structure under different wind conditions. However, it is also necessary to repeat these analyses several times for the parametric study to seek suggestions for specific changes that would improve the dynamic behavior of the structure.

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