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MODAL PARAMETER IDENTIFICATION OF A STEEL LATTICE TOWER

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This paper presents a modal analysis of a lattice steel tower used for telecommunication purposes in Barcarena, Pará, Brazil. Based on the design plans provided by the tower owner, the structure was analysed with SAP2000 software, using different computational models. Some models are quite simple and were developed to allow comparisons with analytical solutions. One of the objectives of this paper is to investigate the quality of the results of SSI (Stochastic Subspace Identification), a modal identification method based only on the response of the structure. Dynamic tests were simulated through the application of arbitrary impacts on the tower nodes. The obtained accelerations, corresponding to arbitrary impulse simulations, were exported to ARTEMIS Testor software, and then, to ARTEMIS Extractor, to obtain the modal parameters of the tower. The importance of this study lies on the benefits provided by previous preparation of the field testing to be executed. At the end of the analyses, despite the adopted simplifications, good correlation between vibration modes was observed, except for model with center symmetry, which presents difficulties in the identification of the modal configuration.

Keywords: Modal Analysis, SAP2000, ARTeMIS, Trussed Metal Tower

1. Introduction

Due to the importance of security and efficiency of telecommunication services, there is an increasingly major concern of public agencies and private companies about maintaining the integrity of structures that serve as support for the transmission equipment, which consist largely of steel structures.

According to CARRIL JÚNIOR (2000), due to the low deadweight of lattice towers, their determinant factor for design is wind action. Consequently, it is crucial to analyze the effects of dynamic behavior on the structure at hand. Therefore, it is more appropriate to conduct a dynamic analysis of the tower, as disregarding dynamic effects may lead the structure to failure. Furthermore, the structure may collapse due to fatigue (LAZANHA, 2003).

The overall objective of this study is to simulate an experimental modal analysis with data obtained computationally, using a finite element software. For this purpose, a dynamic analysis of a steel lattice tower, subject to arbitrary nodal impacts, was performed, and based on the acceleration histories of some structure nodes, ARTeMIS, a commercial program based on the SSI (Stochastic Subspace Identification) method, is then used for identification of the natural frequencies and corresponding vibration modes of the structure.

SSI (Stochastic Subspace Identification) has been used in the identification of modal parameters of large structures subject to environmental vibration with great success. As it is a relatively new method, there is a need for better evaluating the quality of the obtained results, and it is also useful to evaluate the performance of the computer programs that employ this method, and to verify the corresponding accuracy.

The simulation of experimental modal analysis with data obtained computationally eliminates the possibility of errors introduced by the sensors, and/or by the acquisition system, or by the kind of excitation used. In addition, in this methodology, the level of realism of the computational model is less relevant, which allows to better investigate the precision of the method used to identify the modal parameters.

In case of failure of a telecommunication tower, besides significant financial losses directly related to the structure collapse, there also occur losses due to interruption of data transmission, not to mention safety issues due to the large size of the structure.

Located in the City of Barcarena, State of Pará, Brazil, the steel lattice tower used in the study has 80m of height and an equilateral triangular cross section. The side of the triangular section varies from 10.20m at the base to 1.50 m at the top. The truss bars are formed by steel angles of various dimensions.

2. Modal Analysis

Modal analysis allows the determination of the dynamic characteristics of a structural system, namely: natural frequencies and vibration modes. These parameters, in turn, depend on the mass, stiffness and damping matrices of the structure, which can be easily determined through a discretization of the structure based on the finite element method.

For a system of multiple degrees of freedom, the equation which governs the dynamic equilibrium is given by (CLOUGH and PENZIEN, 2003):

$$M\ddot{X} + C\dot{X} + KX = F(t) \tag{1}$$

Where,

- M is the mass matrix
- C is the damping matrix
- K is the stiffness matrix
- $F(t)$ is the vector of nodal forces, defined as a function of time
- $\ddot{X}, \dot{X}, X$ are, respectively, the vectors of accelerations, velocities and displacements of the n degrees of freedom

The vibration modes and natural frequencies are obtained with the structural system vibrating freely without the influence of damping.

$$M\ddot{X} + KX = 0 \tag{2}$$

The answer for the free undamped system is:

$$X = \varphi . sen(\omega_0 t - \alpha) \quad (3)$$

$$\ddot{X} = -\varphi \omega_0^2 \cos(\omega_0 t - \alpha) \quad (4)$$

Where,

- t is the time variable;
- α is the phase angle.
- φ represents the modes of vibration.

The modes of vibration and the natural frequencies of the structure are determined solving an eigenvalue problem. Substitution of equations (3) and (4) in equation (2) results in:

$$\left[K - \omega_0^2 M \right] \varphi = 0 \quad (5)$$

which is a problem of eigenvalues and eigenvectors, where the eigenvalues ω_0 represent the natural frequencies and the eigenvectors φ their corresponding vibration modes (CLOUGH and PENZIEN, 2003).

3. Computational Modal Analysis

In computational modal analysis the modal parameters of the structure are obtained from the numerical solution of the equation of motion in undamped free vibration, according to Equation (5), which is a problem of eigenvalues and eigenvectors. To obtain the modal parameters, SAP2000 was used in the analysis of two models: A beam-column model, called Model 1, and a spatial truss model, called Model 2 (Figure 1). The results are shown in Table 1.

Table 1. Results of computational modal analysis for models 1 and 2.

Model 1			Model 2		
SAP Mode	**Freq. (Hz)**	**Dir.**	**SAP Mode**	**Freq. (Hz)**	**Dir.**
1	2,667	X	1	1,445	X
2	2,667	Y	2	1,445	Y
3	16,795	X	3	3,718	X
4	16,795	Y	4	3,751	Y
5	47,214	Y	5	4,141	local
6	47,214	X	6	4,917	local
7	92,850	Y	7	5,112	torsion
8	92,850	X	8	5,800	X
9	153,609	Y	9	6,248	local
10	153,609	X	10	6,335	Y
11	228,832	X	11	6,520	local
12	228,832	Y	12	6,711	X

4. Computer Simulation of Experimental Modal Analysis

To extract the modal parameters, ARTEMIS, which is based on the stochastic identification method SSI was employed . This method is usually used for extracting modal parameters from measurements under environmental vibration (wind, vehicle traffic, pedestrian walkway, etc.). Thus, through this type of analysis, the modal characteristics of the structure are determined in relation to the data output only ("output-only data”), as opposed to more traditional procedures of experimental modal analysis, where the input is known (Souza, et al, 2008).

The tolerance criteria used for stabilization of the SSI method were 0.5% for frequency, 5% for damping, 5% for the mode and 80 for the order number of the model, in all tests.

The identification of modes is done, in practice, from the stabilization diagram. According to NUNES apud AMADOR (2007), this diagram represents the system description by a number of ways: it increases the number of modes that describe the system and there is a consistency of the frequencies and damping by varying these parameters. According to the author, the idea is that solutions with the same frequency and damping values correspond to the resonances of the real physical system.

ARTEMIS Extractor is a program that performs the extraction of modal parameters from the experimental data, usually recorded with accelerometers. However, it is noteworthy that the purpose of this study was to carry out a computer simulation of an experimental analysis.

In this analysis, half sine wave pulses with very short duration, similar to impacts, were applied at different nodes identified in Figure 1. The response time of the experiment was 300 seconds and the pulses were applied arbitrarily during this time, with different intervals between applications. Ten half sine wave functions with different durations were used.

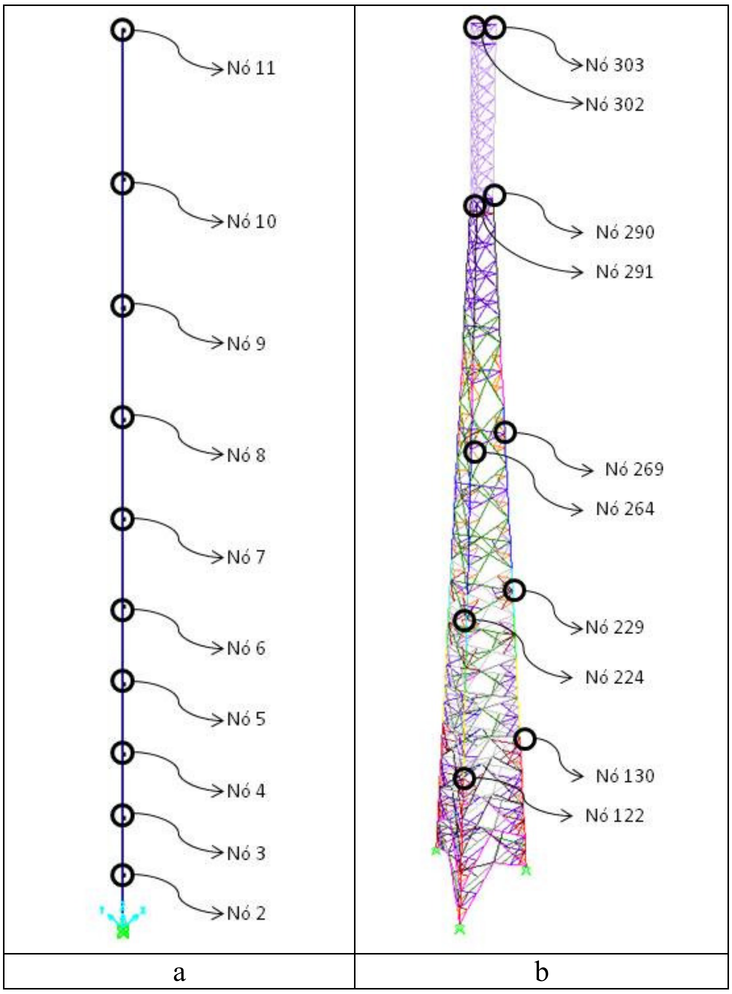

Figure 1. Identification of the nodes where the pulses were applied. a: Model 1 divided in 10 parts, b: Model 2.

5. Correlation between Numerical Model and Simulated Experimental Model

5.1 Frequencies and Vibration Modes

First, we performed the simulation of modal analysis in the ARTeMIS Extractor for Model 1 and two stable modes corresponding to two mode shapes of SAP2000 were identified by the software, as reported in Table 2.

Table 2. Comparison between frequencies for Model 2.

ARTeMIS Extractor		SAP 2000	
Mode	Freq. (Hz)	Mode	Freq. (Hz)
1	2,694	1	2,660
2	16,840	3	16,790

In the modal analysis of ARTeMIS Extractor for Model 3 six vibration modes were found, three of them stable and two unstable. Stable modes presented a good correlation between results obtained in SAP2000, as it can be seen in Table 3. The comparison among the modal shapes is shown in Figure 2.

Table 3. Comparison between frequencies for Model 3.

ARTeMIS Extractor		SAP 2000	
Mode	Frequency	Mode	Frequency
1	1,482	1	1,445
3	3,685	3	3,718
4	3,853	4	3,751
6	6,264	10	6,336

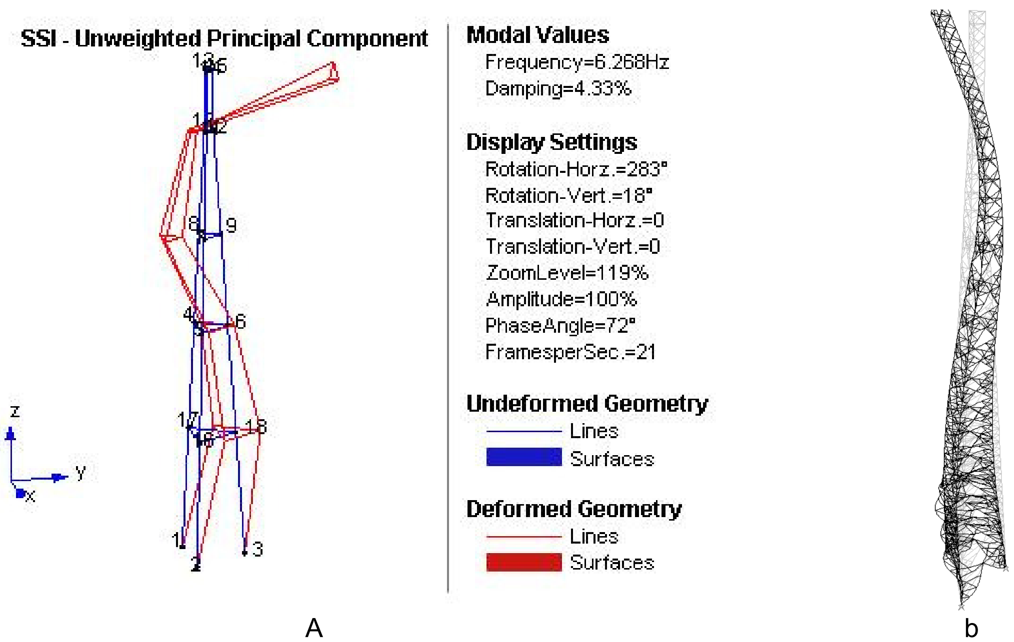

Figure 2. Modal shape for Model 3. a: Mode 6 of ARTeMIS Extractor, b: Mode 10 of SAP2000.

5.2 MAC – Modal Assurance Criteria

The MAC coefficient is the best known criteria used to compare vibration modes obtained by finite element method with experimental tests, analytical representations or, as in this work, experimental simulations of existing models. The MAC coefficient is defined by equation (6):

$$MAC_{ij} = \frac{\left|\left(\phi_i^R\right)^T \phi_j^A\right|^2}{\left(\left(\phi_i^R\right)^T \phi_i^R\right)\left(\left(\phi_j^A\right)^T \phi_j^A\right)} \tag{6}$$

Where,

- ϕ_i^R is the $i°$ reference mode of vibration
- ϕ_j^A is the j numerical mode of vibration.

It is interesting to give a geometric interpretation for the MAC coefficent. For vectors in R3, the MAC corresponds to the square of the cosine of the angle between two vectors. If the vectors are parallel (collinear), the value of the MAC coeficiente is equal to 1, indicating maximum correlation. If the vectors are orthogonal the MAC value is equal to 0, indicating zero correlation.

Moreover, the MAC coefficient cannot ensure that a correct correlation between the vibration modes has been achieved. For example, it is not sufficient to ensure accuracy when a small number of measurement points are considered, or when the finite element model has a small number of nodes. In such cases, some vibration modes associated with different natural frequencies may appear similar or even equal.

In the case of Model 2, modes were considered satisfactory, regarding the MAC coefficients, according to Table 4.

Table 4. Correlation between the modes and the MAC value in Model 2

ARTeMIS Extractor		SAP 2000		MAC
Mode	**Frequency**	**Mode**	**Frequency**	
1	1,482	1	1,445	0,9254
3	3,685	3	3,718	0,8678
4	3,853	4	3,751	0,8806
6	6,264	10	6,336	0,8629

For Model 1, although the frequencies found are very close to the frequencies obtained numerically, the MAC coefficient was not close to unity, as shown in Table 5. It was observed that the mode shapes were not identified independently in x and y directions, which leads to the hypothesis that due to the fact that the model has a square section, and therefore identical frequencies in the x and y directions, the experimental analysis produced a combined mode shape of these two directions (Figure 3). Therefore, a third model (Model 3) was studied, with the same characteristics as Model 1, but with the inertia of a rectangular section.

The same procedure adopted for Models 1 and 2 was applied to Model 3.

Table 5. Correlation between modes and the MAC value in Model 1.

ARTeMIS Extractor		SAP 2000		MAC
Mode	**Frequency**	**Mode**	**Frequency**	
1	2,694	1	2,660	0,660
2	16,840	3	16,790	0,017

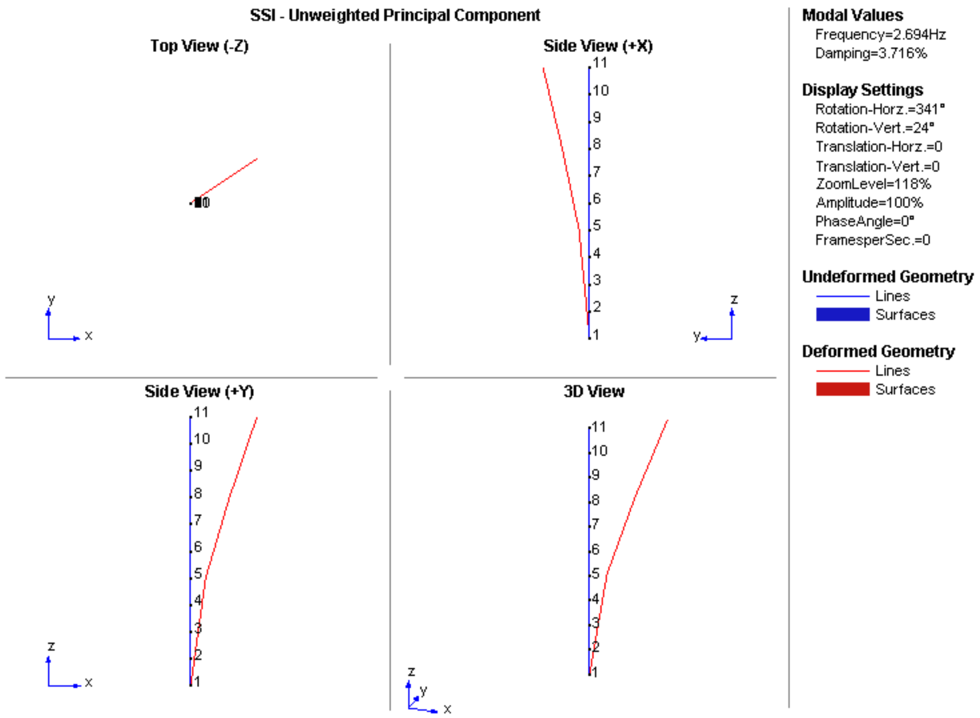

Figure 3. Model 2 – 1st mode, freq = 2,694 Hz – ARTEMIS

After comparing the results obtained with SAP2000 and ARTeMIS Extractor, it could be observed that there was great similarity between the mode shapes. Moreover, it was confirmed that with a rectangular section (Model 3), there was a good correlation between the modes obtained directly from the numerical model and the modes obtained through the numerical simulation of the experimental test, as illustrated in Table 6.

Table 6. Correlation between modes and the MAC value in Model 3.

ARTeMIS Extractor		SAP 2000		MAC
Mode	**Frequency**	**Mode**	**Frequency**	
1	2,674	1	2,660	0,997
2	3,752	2	3,770	0,997
3	16,770	3	16,80	0,973
4	23,660	4	23,75	0,707

Because the value of the nyquist frequency which ARTeMIS used for the analysis of Model 3 was equal to 50 Hz, higher frequencies could not be found.

6. Concluding Remarks

After comparing the results of the program SAP2000 and ARTeMIS Extractor, it was observed that there is a good correlation between the numerical model and the simulated experimental test. It was concluded that the SSI method has good accuracy with respect to identification of frequencies and modes, except in the case of structures with center symmetry.

Thus, because the structure analyzed in Section 2 has center symmetry, it shows repeated natural frequencies with similar mode shapes in different directions and in the case of analysis with the ARTeMIS, using the SSI method, those very similar modes were coupled in the diagonal direction.

Despite the nyquist frequency value was low for Models 1 and 3, the number of modes found was sufficient to verify computationally the good correlation between the simulated experimental test and the numerical models.

To continue the work, it would be interesting to apply a white noise to the response and to consider a greater quantity and variety of arbitrary pulses, in order to better characterize the excitation source; applying a basis displacement in order to simulate an earthquake and; making an analysis with experimental field data.

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