ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

FULL-SCALE EXPERIMENTAL MODAL ANALYSIS OF AN OVERHEAD TRANSMISSION LINE TOWER CROSSING GUAMÁ RIVER IN THE AMAZON REGION

Sandro D. Rescinho Amador*[1], Luis A. Conte Mendes Veloso[1] Remo Magalhães De Souza[1], and Jean Rodrigo F. Aguilera[2]

[1]Graduate Program in Civil Engineering, Federal University of Pará, Brazil
Campus Universitário do Guamá, Prédio do Centro Tecnológico, Sala 232
Rua Augusto Côrrea, 01 CEP 66075-110, Belém, PA, Brasil
[2]Department of Civil Engineering, Pontifical Catholic University of Rio de Janeiro
Rua Marquês de São Vicente, 225, Gávea
Rio de Janeiro, RJ - Brasil - 22453-900
diord@ufpa.br

Abstract

This paper presents the results of a dynamic analysis performed on a steel latticed tower of an overhead transmission line at the Guamá River crossing, located in Eastern Amazon Region, Brazil. The tower lies in the right margin of the river; it is approximately 75 meters high and supports three double conductor bundles which cross an span about 800 meters long. To investigate the dynamic behaviour of the tower, an experimental modal analysis was performed with a set of low-frequency piezo-electric (ICP) accelerometers suitably installed in two cross sections along its height. As it is very difficult to measure magnitude of wind excitation, an output-only modal analysis method based on the stochastic subspace identification (SSI) method was employed, to extract the eigenfrequencies and corresponding mode shapes and damping ratios. It was observed that the method was very efficient for identification of this structure as it was capable to detect two very close modes (around 1.8 Hz). A further comparison between experimental and theoretical dynamic behaviours showed that, due to the simplifications in modelling the cables, the results are in good agreement only for the first three modes of vibrations (from a total of eight analysed modes).

Eds.: Av. Augusto Corrêa, 01, Campus do Guamá, Centro Tecnológico, Sala 236, Belém, PA, Brasil.

1 INTRODUCTION

Interest on structural behaviour of electrical transmission lines has been increased in the latest decades in Brazil, since its transmission system is becoming older. In the Amazon region, for instance, where the overhead lines pass through the rainforest and overcome great obstacles such as large river crossings, cases of collapse of latticed towers have occurred due to wind gusts. One of the most notorious of these cases was the collapse of one tower of the Tapajós River crossing, located in western Pará state, Brazil. A 160 meter high latticed tower collapsed after exceptionally violent wind gusts, leading to interruption of energy supply in the region. Other studies on the dynamic behaviour of the latticed structures under ambient excitation in Amazon region are found, for instance, in [5] and [6].

This paper describes the dynamic analysis of a steel latticed tower of a 230 kV overhead transmission line at the Guamá River crossing, located in Eastern Amazon Region, Brazil. The study aims to investigate the dynamic behaviour of these structures under Amazon's environment. For this purpose, an output-only experimental modal analysis was performed based on the theory introduced by [1], [2] and [3], and the identified modal parameters were compared to theoretical results of a Finite Element (FE) analysis.

2 DESCRIPTION OF THE STRUCTURE

Guamá River is about 1.600m wide at the point where it is crossed by the overhead line under study. The crossing consists of five self-supporting towers: one suspension tower standing in the middle of the river, two suspension towers located at each margin, and two adjacent anchor towers (located inland). The towers support three double conductor bundles.

The tower under investigation is located at the right margin of the river, and is approximately 75 meters high. The structure is composed of steel bars with "L" shaped sections (figure 1).

Figure 1 – Overhead electrical transmission line tower at the right margin of Guamá River.

3 EXPERIMENTAL MODAL ANALYSIS

The experimental modal analysis was performed with six low frequencies accelerometers. The time histories signals were processed in SISMEC (System for Output-only Modal Analysis of Civil Engineering Structures), which is a GUI toolbox developed in MATLAB platform for an output-only experimental modal analysis, as part of the M.Sc. thesis of the first author. The next section presents a brief description of this method. A detailed presentation of the corresponding theory can be found in [1], [2] and [3].

3.1 Stochastic state-space model

Since input information is not available in an output-only vibration experiment, it is not possible to distinguish between the input u_k and noise, though these components are substituted by the stochastic components w_k and v_k, yielding the following stochastic state-space model in discrete time:

$$\begin{aligned} x_{k+1} &= Ax_k + w_k \\ y_k &= Cx_k + v_k \end{aligned} \tag{1}$$

Where x_k, y_k, A and C are the discrete-time state vector, discrete output vector, discrete state matrix and output matrix, respectively.

For system identification purposes, a suitable way to arrange the output data signals of a vibration experiment is to assemble a block Hankel matrix, scaled by $\sqrt{N}$, with $2i$ rows and N columns.

$$H^{ref} = \frac{1}{\sqrt{N}} \begin{bmatrix} y_0^{ref} & y_1^{ref} & \cdots & y_{N-1}^{ref} \\ y_1^{ref} & y_2^{ref} & \cdots & y_N^{ref} \\ \cdots & \cdots & \cdots & \cdots \\ y_{i-1}^{ref} & y_i^{ref} & \cdots & y_{i+N-2}^{ref} \\ \hline y_i & y_{i+1} & \cdots & y_{i+N-1} \\ y_{i+1} & y_{i+2} & \cdots & y_{i+N} \\ \cdots & \cdots & \cdots & \cdots \\ y_{2i-1} & y_{2i} & \cdots & y_{2i+N-2} \end{bmatrix} = \left(\frac{Y_p^{ref}}{Y_f} \right) \begin{matrix} \updownarrow ri \\ \updownarrow li \end{matrix} \qquad \frac{"past"}{"future"} \tag{2}$$

This matrix is divided into two blocks rows Y_p^{ref} and Y_f. The first *ri* rows contains past reference output data and second *li* rows holds the future output data. The index *r* refers to the number of reference sensors, and *l* denotes the number of all sensors used in the vibration experiment. An extended absorbability matrix is defined as:

$$O_i = \left\{ C^T \quad (CA)^T \quad (CA^2)^T \quad (CA^{i-1})^T \right\}^T \tag{3}$$

This is a *li by n* matrix, where *A* is the state matrix and *C* is the output matrix. The index *n* denotes the model order, and the pair {*A*, *C*} is assumed to be observable, which means that the modal parameters are observed in the output data of a vibration experiment [1].

3.2 Data-driven stochastic subspace identification (SSI-DATA) method

The experimental modal analysis of the latticed structure crossing Guamá River was performed using the SSI-DATA method. The advantages of this method lie upon the innovations proposed by [1] and [2], where projection of the future outputs into the row space of the past outputs is the key step. In this section, only a brief description of the SSI-DATA method is showed. Further details are found, for instance, in [7].

3.2.1 Kalman Filter States

Through the definitions of Kalman filter, a state input vector $\hat{x}_{k+1}$ is estimated from the observations of the output data up to time *k* [1]. More details about Kalman states can be found, for instance, in [1] and [2]. These estimates are gathered to assemble the Kalman filter estates sequence $\hat{X}_i$.

$$\hat{X}_i \equiv (\hat{x}_i \quad \hat{x}_{i+1} \quad \cdots \quad \hat{x}_{i+j-1}) \tag{4}$$

3.2.2 Implementation

The implementation of SSI-DATA method begins by factorizing the Hankel matrix (2) into a QR product.

$$H^T = \left(\frac{Y_p^{ref}}{Y_f} \right)^T = RQ^T; \qquad H = QR^T \tag{5}$$

where Q is an orthonormal matrix, and R is a lower triangular matrix.

$$H = \begin{matrix} & & ri & r & l-r & l(i-1) & & j \to \infty & & \\ & & \leftrightarrow & \leftrightarrow & \leftrightarrow & \leftrightarrow & & \leftrightarrow & & \\ ri & \updownarrow & R_{11} & 0 & 0 & 0 & & Q_1^T & \updownarrow & ri \\ r & \updownarrow & R_{21} & R_{22} & 0 & 0 & & Q_2^T & \updownarrow & r \\ l-r & \updownarrow & R_{31} & R_{32} & R_{33} & 0 & & Q_3^T & \updownarrow & l-r \\ l(i-1) & \updownarrow & R_{41} & R_{42} & R_{43} & R_{44} & & Q_4^T & \updownarrow & l(i-1) \end{matrix} \tag{6}$$

The introduction of projection of the row space of future outputs onto the row space of the past reference outputs in equation (7) is the key step towards SSI-DATA method.

$$\mathsf{P}_i \equiv Y_f / Y_p^{ref} \equiv Y_f Y_p^{ref^T} (Y_p^{ref} Y_p^{ref^T})^{\dagger} Y_p^{ref} \tag{7}$$

Where $(\bullet)^{\dagger}$ denotes de Moore-Penrose inverse of a matrix.

The main theorem of stochastic subspace identification [3] shows that this projection can be factorized into the observability matrix (3) and the Kalman filter state sequence (4).

$$\mathsf{P}_i^{ref} = O_i \hat{X}_i = \begin{pmatrix} R_{21} \\ R_{31} \\ R_{41} \end{pmatrix} Q_1^T \tag{8}$$

These factors can also be determined through the employment of SVD on the projection.

$$\mathsf{P}_i^{ref} = U_1 S_1 V_1^T, \quad O_i = U_1 S_1^{1/2}, \quad \hat{X}_i = O_i^{\dagger} \mathsf{P}_i^{ref} \tag{9}$$

The definition of another projection from the shifted past and future outputs is needed for calculation of the system matrices *A* and *C*.

$$\mathrm{P}_{i-1}^{ref} \equiv Y_f^- / Y_p^{ref+} = (R_{41} \quad R_{42}) \begin{pmatrix} Q_1^T \\ Q_2^T \end{pmatrix} \tag{10}$$

Similar to equation (8), this new projection can be factorized as:

$$\mathrm{P}_{i-1}^{ref} = O_{i-1} \hat{X}_{i+1} \tag{11}$$

where O_{i-1} is determined by deleting the last l rows of O_i. The shifted Kalman filter state sequence $\hat{X}_{i+1}$ is computed as:

$$\hat{X}_{i+1} = O_{i-1}^{\dagger} \mathrm{P}_{i-1}^{ref} \tag{12}$$

The system matrices A and C can be calculated from the set of equations (13).

$$\begin{pmatrix} \hat{X}_{i+1} \\ Y_{i|i} \end{pmatrix} = \begin{pmatrix} A \\ C \end{pmatrix} \hat{X}_i + \begin{pmatrix} \rho_w \\ \rho_v \end{pmatrix} \tag{13}$$

Where $Y_{i|i}$ matrix is calculated by extracting the intermediate l block rows from the Hankel matrix (6).

$$Y_{i|i} = \begin{pmatrix} R_{21} & R_{22} & 0 \\ R_{31} & R_{32} & R_{33} \end{pmatrix} \begin{pmatrix} Q_1^T \\ Q_2^T \\ Q_3^T \end{pmatrix} \tag{14}$$

As ρ_w and ρ_v are the residuals uncorrelated with $\hat{X}_i$, the system matrices A and C are calculated by solving the overdetermined system of equations (15) in a least-squares sense.

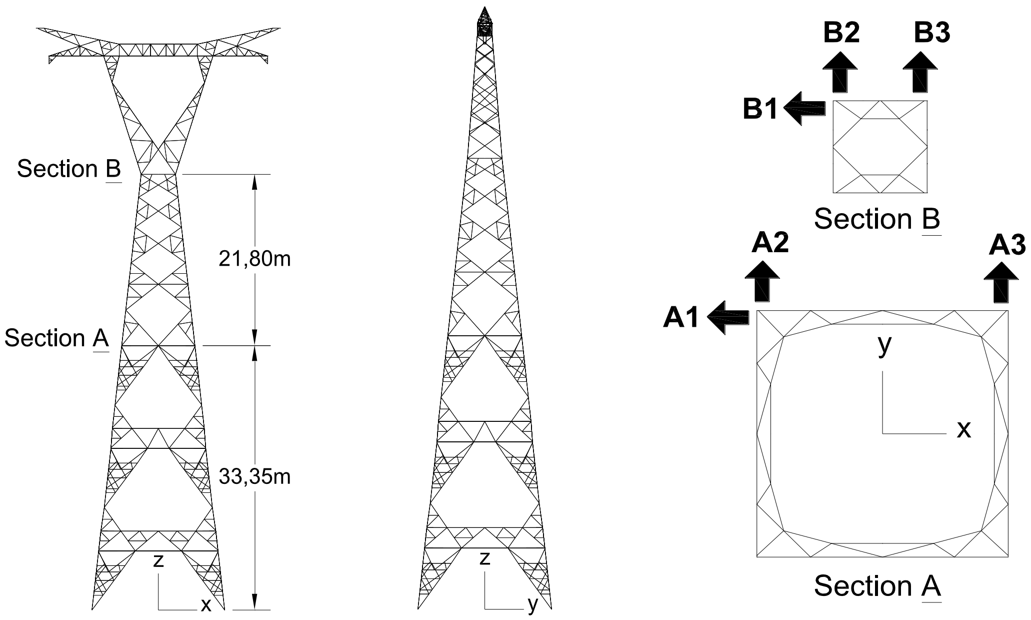
$$\begin{pmatrix} A \\ C \end{pmatrix} = \begin{pmatrix} \hat{X}_{i+1} \\ Y_{i|i} \end{pmatrix} \hat{X}_i^{\dagger} \tag{15}$$

Finally, the computation of the discrete poles Λ_d and the corresponding observed mode shapes V is accomplished through the eigenvalue decomposition of the matrix A.

$$A = \Psi \Lambda_d \Psi^{-1}; \quad V = C\Psi; \tag{16}$$

3.3 Data Acquisition

In the vibration experiment of the transmission line tower, six low frequency piezo-electric accelerometers were used to measure acceleration. The sensors were suitably installed in two cross sections along the height of the tower. These sections are denoted as **A** and **B** as shown in figure 2. It was admitted that these sections approximately behaved as a rigid diaphragm.



(a) Elevation (front) (b) Elevation (side) (c) Cross sections of the tower

Figure 2 – Location of the accelerometers along the height of the tower

The structure was continuously monitored for five hours during a windy day at a sampling rate of 100 Hz. The collected data was filtered out by a digital Chebyshev type low-pass filter with a cutoff frequency of 5 Hz, and re-sampled at a lower frequency of 12.5 Hz. A typical filtered time data signal and its corresponding spectrum are showed in figure 3.

A stability diagram [4] was constructed by ranging the model order from 2 to 80, and using the sensors B1 and B2 as references. The natural frequencies, damping ratios and corresponding mode shapes were easily determined by moving the mouse cursor over the stable poles. An illustration of the identification procedure and a detail of two close-spaced modes around 1.8 Hz are shown in figure 4.

The estimated mean values of eigenfrequencies and damping ratios and their corresponding standard deviations for the first eight modes are shown in table 1, as well as the theoretical eigenfrequencies from the FE analysis. These values are estimated for each mode from a sample of 10 stable poles selected in the stability diagram.

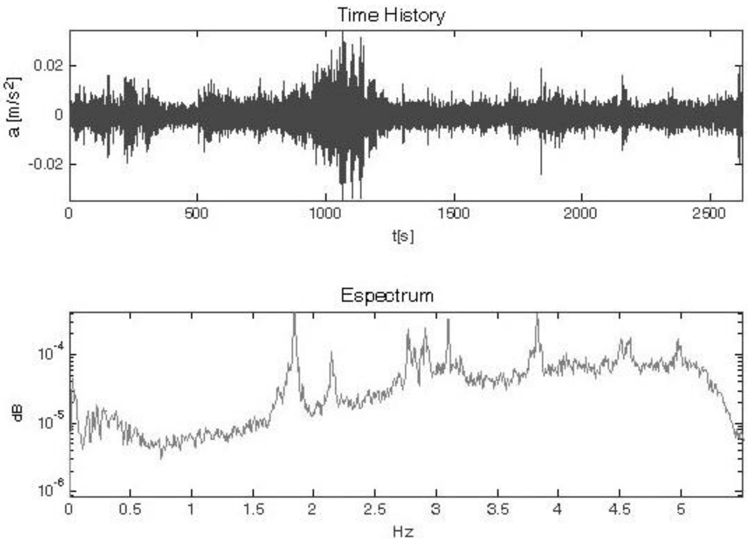


Figure 3 – Example of a typical measured signal and its corresponding spectrum

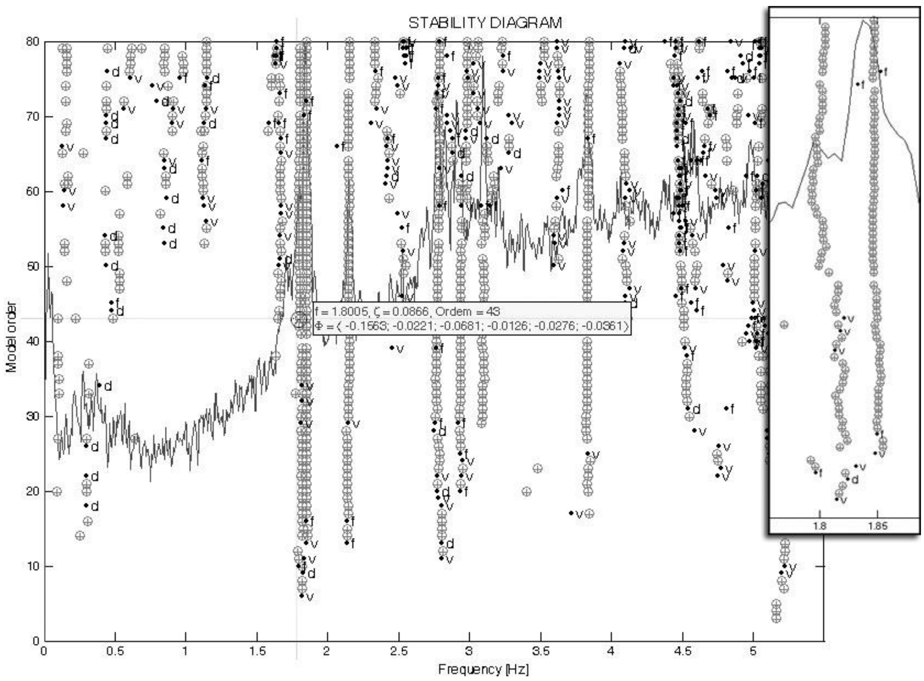


Figure 4 – Stabilization plot. The criteria are: 1% for frequencies, 5% for damping ratio, 1% for vectors (MAC). The used symbols are: ⊕ *- stable pole;* .v *- stable frequency and vector;* .d *– stable frequency and damping;* .f *– stable frequency.*

.

Table 1 – Mean values of the eigenfrequencies, damping ratios and standard deviations

Mode	SSI-DATA results				FE results
	Eigenfrequencies		Damping ratios		Eigen-frequencies
	$\bar{f}(Hz)$	$\sigma_f(Hz)$	$\bar{\zeta}(\%)$	$\sigma_\zeta(\%)$	
1	1,666	0,007	0,1801	1,9707	1,693
2	1,798	0,005	0,0820	0,1611	1,781
3	1,847	0,001	0,0435	0,0755	1,828
4	2,147	0,003	0,0741	0,2682	3,244
5	2,774	0,002	0,0685	0,0881	3,519
6	2,936	0,003	0,0743	0,1269	3,634
7	3,094	0,006	0,1223	0,3554	3,987
8	3,829	0,001	0,0335	0,0320	4,146

4 CONCLUSIONS AND FURTHER INVESTIGATIONS

The experimental and FE modal parameters were in very good agreement for the first three modes. However, it can be observed that the results do not match for the five remaining modes, which probably means that the FE model could not represent precisely the behaviour of the structure at higher frequencies. One possible explanation for this discrepancy is that only the estimated mass of the conductor bundles was introduced in this FE model at their supporting joints, whereas the corresponding stiffness was not considered in this primary model. A new FE model considering the stiffness and large displacements of the cables by using the co-rotational formulation [5] is under creation for a more accurate investigation.

5 REFERENCES

[1] B. Peeters, G. De Roeck, "Reference Based Stochastic Subspace Identification for Ouput-only Modal Analisys", 1999, Mechanical System and Signal Processing, 13(6), 855-878.

[2] B. Peeters, "System Identification and Damage Detection in Civil Engineering", Ph. D. thesis, Leuven, Belgium, 2000.

[3] P. Van Overschee and B. De Moor, “Subspace Identification for Linear Systems - Theory Implementation Applications". Kluwer Academic Publishers, 1996.

[4] R. J. Allemang, “Vibrations: Experimental Modal Analysis”, Course Notes, Revision 7, Structural Dynamics Research Laboratory, University of Cincinnati, OH, USA, [http://www.sdrl.uc.edu], 1999.

[5] R. M. De Souza, “Force-based Finite Element for Inelastic Large Displacement Analysis of Frames”, Ph. D. Thesis, University Of California at Berkeley, California, USA, 2000.

[6] S. D. R. Amador.; R. M. De Souza, J. F Rodrigues, M. R. Teixeira, , “Computational and Experimantal Dynamic Analysis of the Steel Access Bridge to Bulk Liquid Terminal of the Port of Vila do Conde - PARA, BRASIL”, Proceedings of XXV Iberian Latin Amarican Congress on Computational Methods in Engineering (CILAMCE), Recife, PE, Brazil, 2004, (in portuguese).