Vibration assessment of the International Guadiana Bridge

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ABSTRACT: The paper describes the development of a monitoring program for a cable-stayed bridge and resumes the major dynamic properties identified from a series of test campaigns conducted on the bridge, which are also correlated with results from a numerical analysis. Some aspects of the current dynamic behavior of the bridge under ambient excitation are discussed, considering in particular the large cable vibrations that are frequently observed.

1 INTRODUCTION

The International Guadiana Bridge (Fig. 1) is a concrete cable-stayed bridge spanning the Guadiana River close to the border with Spain, at the southern part of Portugal. The bridge was designed by Câncio Martins (1992) and opened to traffic in 1991. Given the relatively severe wind and high seismic risk characteristics of the bridge site, extensive studies were developed prior, during and after construction (Branco, 1987; LNEC, 1992; Branco et al., 1991, 1993;). Despite the generally good performance under normal traffic and ambient conditions, the stay cables soon proved to be vulnerable to wind excitations, fact that is in a great deal associated with the absence of protection with a pipe of the individual parallel strands that form each stay cable, and that results in the occurrence of frequent oscillations of high amplitude, accompanied by a significant "rattling noise". Furthermore, a study developed at commissioning stage by Pinto da Costa et al. (1994) pointed to some vulnerability of certain cables to the so-called phenomenon of parametric excitation.

Having the purpose of assessing the current condition of the bridge in terms of the actual dynamic behaviour, characterising in particular the possible different sources of cable vibration and defining as a long-term objective the possible detection of damage, a monitoring program has been developed centred on this bridge. This program includes the development of a series of test campaigns under normal traffic use, as well as the installation of a monitoring system, which will allow the continuous observation of relevant physical quantities from a remote central located at the University.

The current paper describes the essential features of the monitoring system under development and systematises the most relevant dynamic parameters and characteristics of observed vibration that have been identified on the basis of several ambient vibration test campaigns. The major dynamic parameters are correlated with results of a numerical analysis of the bridge.

Figure 1. View of Guadiana Bridge (Câncio Martins, 1992).

2 BRIDGE DESCRIPTION

The International Guadiana Bridge is a partial suspension cable-stayed bridge with a prestressed concrete deck, formed by a central span of 324m, two lateral spans of 135m and two transition spans of 36m. The two A-shaped towers reach a height of 100m above the foundations and have a concrete box section. The 18m wide deck has a prestressed concrete box section with 2.5m depth and is partially suspended by the towers and by 64 pairs of cables arranged in a semi-fan. The stay cables are formed by bundles of 22 to 55 15mm monostrands, which are clamped at mid-length or at the thirds of the length by collars.

3 VIBRATION ASSESSMENT

The installation of a monitoring system on a bridge requires a definition of objectives and the previous knowledge of the intervals of variation of the physical quantities of interest.

In the current case, one of the major objectives is the identification of the major sources of cable vibration. Given that these oscillations are clearly associated with the wind, the identification of the patterns of vibration requires a systematic observation of cable oscillation and wind velocity and direction. On another hand, considering the possibility of parametric excitation, i.e., of cable oscillations triggered by the vibration of the deck, induced by wind and traffic, it is essential to measure deck accelerations too. An important issue in terms of the long-term behaviour of the bridge is the possibility of premature failures of some strands by fatigue, in consequence of repeated excessive vibration occurrences. For this purpose, a direct measure of the levels of installed tension in cables is of interest. Additional measures of temperature and strain at relevant sections of the bridge are devised for correlations with dynamic properties and for characterisation of traffic loads.

Having these aspects into consideration, the current Section presents a summary of measured properties of the bridge, and discusses the major specifications and characteristics traced for the monitoring system under development. Finally, some results of identification of modal parameters are presented, which are used to validate numerical models.

3.1 *Vibration condition*

The data analysed in this paper was collected in two measurement campaigns that took place in March 2003 and May 2004, under normal traffic use. The weather condition registered during measurements was generally considered good. Yet multiple events of large oscillation of the stay cables were registered.

In order to indirectly evaluate the tension installed in stay cables, high sensitivity piezoelectric accelerometers were mounted on the deviator guides, at a height of around 2m from deck level. Using a portable Fourier analyzer, average power spectral density estimates (PSDs) of the ambient vibration response were collected, which allowed the identification of the fundamental vibration frequencies and, consequently, of the installed cable tensions, based on the vibrating chord theory. Several of the cables that temporarily exhibited large vibrations were further investigated, by simultaneous measurement of ambient response at the deck anchorage and at the deviator guide, accompanied by a registration of wind velocity and direction. Figure 2 shows some details of the instrumentation and an example of an obtained PSD estimate. Figure 3 shows PSD estimates obtained simultaneously at one stay cable of the central span and at the deck level, close to 1/3 span for the vertical plane measurements. Table 1 resumes the values and intervals of variation of global bridge and cable frequencies, accelerations and of average wind velocity observed during measurements.

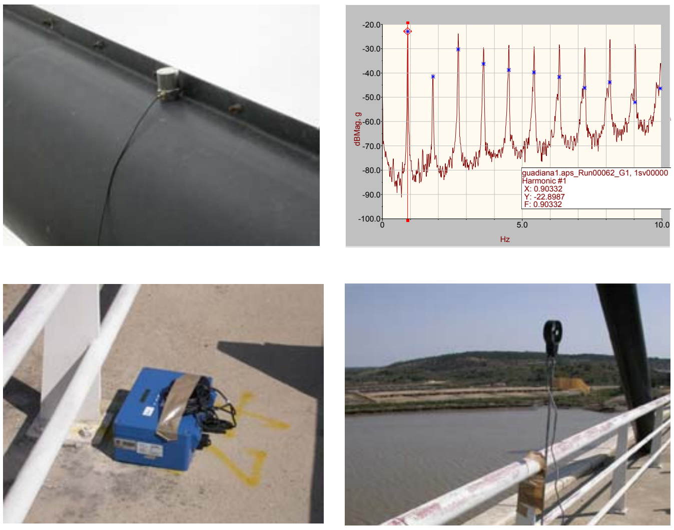

Figure 2. Examples of cable, deck and wind measurements.

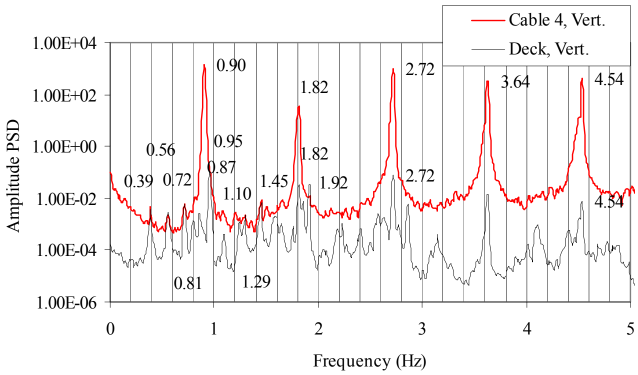

Figura 3. Simultaneous PSD estimates at deck and cable 4.

It can be noticed from that table that deck accelerations are generally very low, the vertical component being one order of magnitude higher than the longitudinal component, and around five times the lateral component. On the contrary, cable accelerations measured at a distance of about 2.5m the deck anchorage present a wide range of values and can reach around one hundred times the vertical deck acceleration, corresponding to maximum amplitudes of oscillation of around 0.50m (1.0m peak-to-peak). It should be noticed that these oscillations occurred for moderate average wind velocities no greater than 14m/s. As for the periodicity and patterns of cable vibration occurrences, various situations were identified, which are clearly correlated with wind velocity and direction, involving different stay cables and presenting different characteristics. It could however be noticed that moderate oscillations occur almost systematically for moderate wind velocities in the range 10-15m/s, involving a significant number of cables. Particular situations were also detected in which one or a group of stay cables (normally, amongst the largest of the central span, or the mid-length cables of lateral spans) suddenly started vibrating very strongly and kept oscillating for various hours after the wind velocity significantly reduced, or else modified the amplitude of oscillation with a slight modification of the wind direction. It is still relevant to notice that the range of fundamental frequencies of the stay cables clearly contains frequencies that are multiple or sub-multiple of global bridge frequencies, meaning that conditions for the occurrence of parametric excitations may be met for particular stay cables (Caetano & Cunha, 2003).

Table 1. Intervals of variation of some physical quantities.

Physical quantity	Interval of variation
Deck acceleration (m/s^2)	0.012-0.048(long.); 0.025-0.069 (lat.); 0.101-0.389 (vert.)
Cable acceleration (m/s^2)	0.4-10
Average wind velocity	..- 14m/s
Fundamental cable frequencies (Hz)	0.72-2.97
Fundamental bridge frequencies (Hz)	0.391 (vert.); 0.537 (lat.); 1.445 (torsion)

3.2 *Monitoring system*

Considering the vibration characteristics systematised above, a monitoring system is being developed, following the instrumentation plan schematically represented in Fig. 4. Accordingly, the measurement system comprehends the following types of sensors: accelerometers, one anemometer, magneto-elastic sensors, one or more video cameras, temperature sensors and electric strain gages. A significant part of the sensors to employ are accelerometers, which constitute at the current state-of-art the motion sensors of highest sensitivity and lowest cost. Given the different amplitudes of vibration experienced by the deck and cables, different types of sensors are expected: force balance type accelerometers are the most convenient sensors for deck motion measurements, due to the low frequency range of interest (0.39-5Hz) and the high sensitivity required. Piezoelectric accelerometers will be used for stay cable measurements, given that these sensors are less demanding than the force balance sensors in terms of powering, and no site baseline correction is needed. Some of the cables instrumented with accelerometers will also have installed magneto-elastic sensors, which will provide a direct measure of cable tension, after convenient site calibration. These sensors have been developed at the Comenius University (Jarosevic & Chandoga, 1994).

Another innovative component of the monitoring system consists in the use of video cameras as sensors. The use of these cameras can be made at two levels: (i) at a first level, the image will be used for remote contact with the structure, allowing for the long distance activation of the acquisition system whenever large oscillations are observed at particular stay cables; (ii) at a second level, and using image processing techniques developed at FEUP, the amplitudes of oscillation of certain cables will be quantified.

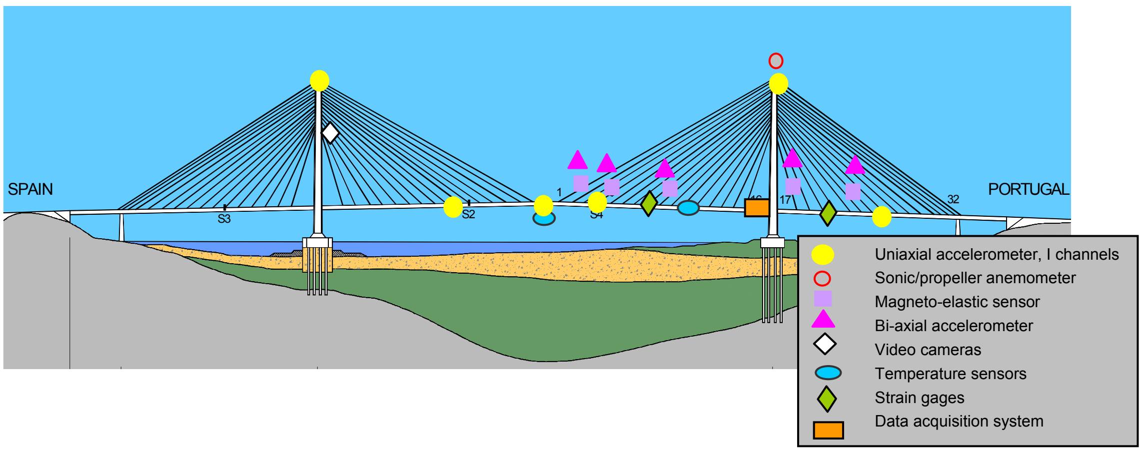

Figure 4. Monitoring plan.

An anemometer will be installed at the top of one tower. The system will be complemented with a set of temperature sensors and strain gages. A total of 64 measurement channels are expected.

The data acquisition system presently under development incorporates a few innovative components, which will allow an increased efficiency at reduced implantation costs. The multi-sensorial system incorporates a technology that allows the replacement of individual electric cables associated with each sensor or set of sensors, by one only electrical cable. This cable links together all the system sensors and connects to a central station, located inside the deck, close to one of the towers, and will be used to provide electrical current to all or part of the sensors, to develop a synchronised sampling and to transmit the measured signals. These signals will be conditioned and digitised close by the sensors, in order to guaranty a high signal/ noise ratio. The measurement chain will be complemented with the development of a computational platform where the control and programming of measurements will be performed. This system will communicate remotely with FEUP for transmission of data and modification of the parameters of acquisition.

3.3 *Dynamic properties*

The most relevant dynamic parameters of the bridge were identified on the basis of an ambient vibration test. Given the low level of signals, the frequency range of interest and the closeness between some relevant natural frequencies, a detailed analysis was required. For this purpose a set of four tri-axial 18-bit strong motion recorders were used. These sensors operate in a synchronised form through GPS units, after initial programming by a laptop, therefore providing an efficient form of developing measurements at many sections along the bridge.

The test scheme adopted was based on the consideration of two reference recorders located close to the third of the central span, at section 17 (Fig. 5), the other two records being successively positioned at the upstream and downstream sides of the deck, at each of the sections 1 to 27 along the deck, and at two levels at each of the towers (sections 28 and 29).

For each setup, time series of 21 minutes were collected, at a sampling frequency of 100Hz. The full test was developed in two and a half days. During this period, the wind velocity at deck level was monitored, using a propeller anemometer. Average wind velocities of 2-14m/s were recorded.

The identification of modal parameters was performed using the classical peak-picking method, after combination of upstream and downstream signals, to separate bending and torsional components. Figure 6 presents Average Normalised Power Spectral Density (ANPSD) functions that were used for identification of natural frequencies.

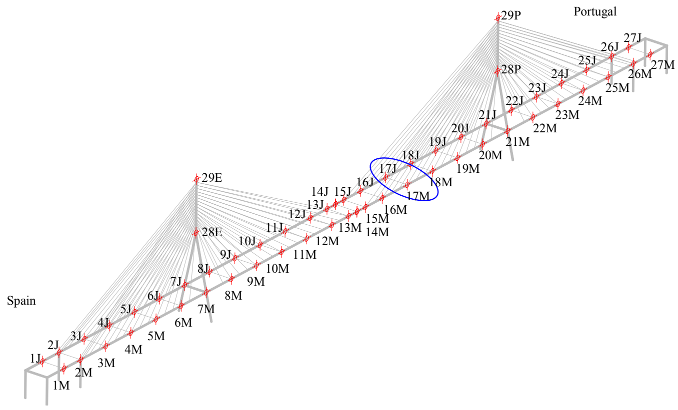

Figure 5. Measurement sections for ambient vibration test.

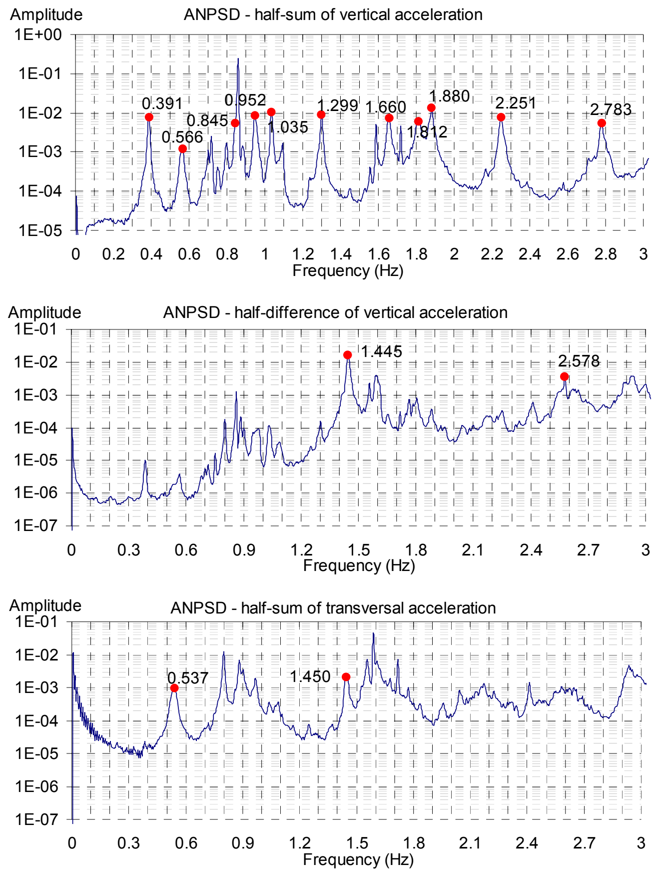

Figure 6. Average Normalised Power Spectral Density functions for vertical and lateral directions.

The presence of a significant number of peaks in the spectral estimates evidences, not only the closeness between successive global mode frequencies (marked and labelled in Fig. 6), but also the contribution of cable vibration, that was very significant for the highest levels of wind velocity. This effect is well evidenced in Fig. 7, where PSD estimates were obtained at the reference section using records collected at average wind velocities of 2m/s, 10m/s and 14m/s.

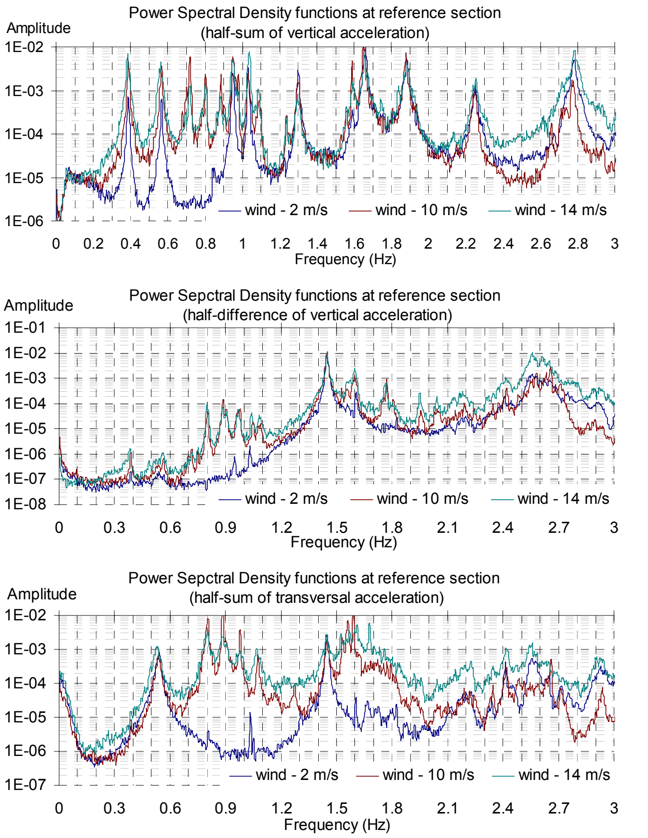

Figure 7. Power Spectral Density functions at reference section at three wind velocity levels.

Figures 8 to 10 represent some of the identified modal configurations associated with the most relevant natural frequencies. In those figures the symbols • define the position of the towers and intermediate supports. Due to the significant interaction observed between some global vibration modes and with cable vibrations, more sophisticated algorithms were explored to provide a better identification of modes, namely the Enhanced Frequency Domain Decomposition (EFDD) and the data driven Stochastic Subspace Identification (SSI) methods. These methods provided also estimates of damping ratios (Magalhães, 2004).

Comparing natural frequencies and modal shapes identified based on the three different methods, no significant differences were found, provided that particular care was taken in the application procedures. As for estimates of damping, Table 2 systematises the values obtained using the EFDD method, which show a certain dispersion. This dispersion is however expected, not only due to the intrinsic nature of damping and to the stochastic character of the identification algorithms, but also due to the variation of certain parameters, like wind or temperature, that strongly affect its value. In fact, the simple analysis of the PSD functions represented in Figure 7 for three different wind velocities, shows a progressive enlargement of the curves with the wind velocity increase at some resonances, corresponding to increasing damping ratio estimates of the corresponding modes. The variation with wind velocity of damping ratio estimates is shown in Table 3 for the first vertical, lateral and torsional modes.

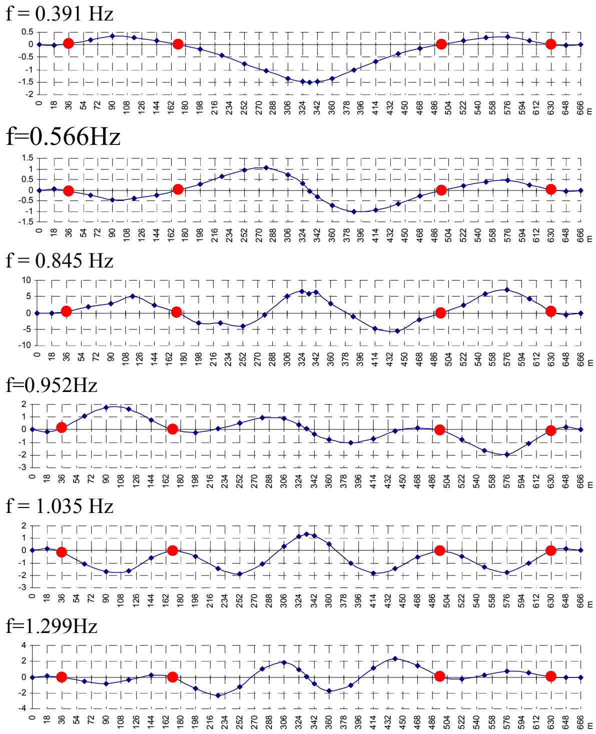

Figure 8. Identified vertical vibration modes.

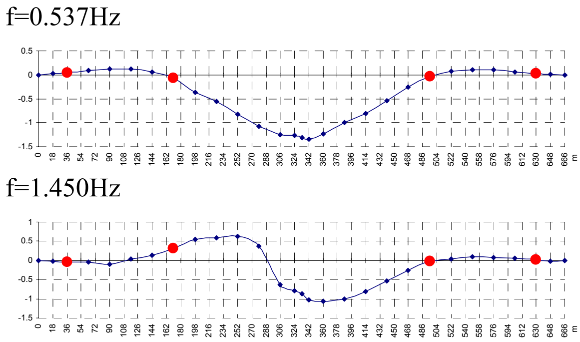

Figure 9. Identified lateral vibration modes.

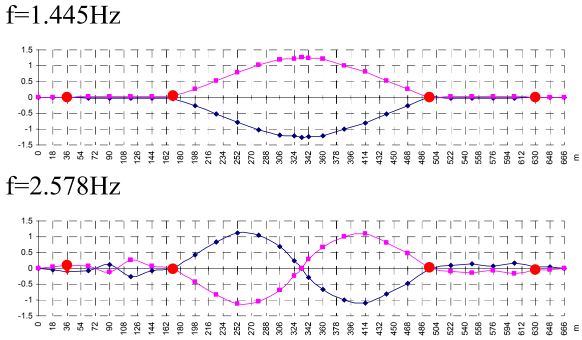

Figure 10. Identified torsional vibration modes.

Table 2. Calculated and identified natural frequencies.

Mode number	Frequency (Hz)		Damping ratio (EFDD) (%)		Type of mode*
	Calc.	Ident.(P.P)	ξ	σ_ξ	
1	0.377	0.391	1.37	0.41	1st VS
2	0.508	0.537	2.23	0.79	1st LS
3	0.521	0.566	1.2	0.45	1st VAS
4	0.778	0.845	-	-	2nd VS
5	0.884	0.952	0.69	0.25	2nd VAS
6	0.963	1.035	0.51	0.12	3rdVS
7	1.193	1.299	0.54	0.11	3rd VAS
8	1.222	1.450	-	-	1st LAS
11	1.493	1.445	0.47	0.16	1st T
12	1.506	1.660	0.63	0.28	4th VS
14	1.684	1.812	-	-	4th VAS
15	1.786	1.880	0.65	0.25	5th VS
20	2.140	2.251	0.59	0.22	5th VAS
23	2.644	2.783	0.46	0.53	6th VS
24	2.682	2.578	1.48	0.19	2nd T

* V: Vertical; S: Symmetric; AS: Anti-symmetric; L: Lateral; T: Torsional

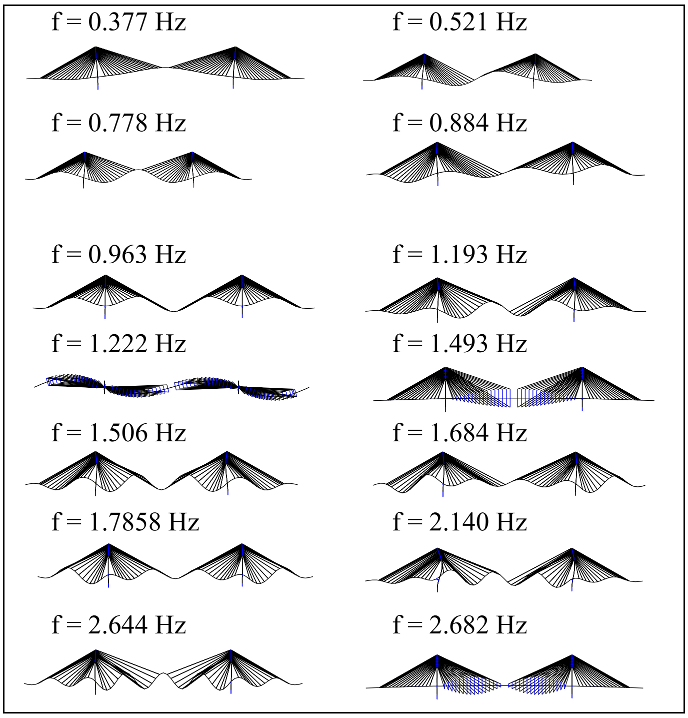

Figure 11. Calculated modal shapes.

Table 3. Variation of ξ with wind velocity.

Wind vel.	1st vertical mode	1st lateral mode	1st torsional mode
2m/s	0.95%	1.84%	0.37%
9m/s	1.43%	2.28%	0.51%
14m/s	1.95%	2.43%	0.47%

Table 2 and Figure 11 summarise the modal parameters obtained from the numerical modelling of the bridge and provide a comparison with experimental data, which shows a good agreement. The identified natural frequencies of in-plane bending and lateral modes are generally slightly higher than the corresponding numerical values. The contrary occurs for the two torsional modes, fact that is possibly associated with insufficient restriction of rotation over the tower supports.

4 CONCLUSIONS

The paper describes the studies developed on a cable-stayed bridge with the purpose of assessing the corresponding dynamic behavior. These comprehend the development of a monitoring system for systematic observation of vibration events and future detection of damage, and a full characterization of the current dynamic properties, to be used as reference. These properties, identified on the basis of an ambient vibration test, are used to validate a numerical model. It is shown that some vibration modes have an increased damping ratio for higher wind velocities.

ACKNOWLEDGEMENTS

The present research has been developed in the context of the Project POCTI/ECM/46475/2002, Vibrations in Cable-stayed Bridges". The authors acknowledge the support of this project, funded by the Portuguese Science Foundation (FCT).

REFERENCES

Branco, F. 1987. Special Studies for the Cable-Stayed International Guadiana Bridge. *Proceedings of the International Conference on Cable-Stayed Bridges*, Ed. W. Kanok-Nukulchai, Bangkok, vol. 2, pp. 1182-1195.

Branco, F. ; Azevedo, J., & Proença, J. 1991. Dynamic Testing of the International Guadiana Bridge (in Portuguese), *CMEST EP Report 35/91*, Lisbon.

Branco, F. ; Azevedo, J., Ritto Correia, M. & Campos Costa, A., 1993. Dynamic Analysis of the International Guadiana Bridge, *Structural Engineering International*, IABSE, no. 4, pp. 240-244.

Caetano, E. & Cunha, A. 2003. Identification of Parametric Excitation at the International Guadiana Bridge. *International Conference on Cable Dynamics*, Santa Margherita, Italy.

Câncio Martins, J. 1992. The International Guadiana Bridge at Castro Marim" (in Portuguese), in Eds. J. Almeida Fernandes & L. Oliveira Santos, *Guadiana and Arade Cable-Stayed Bridges*, LNEC, pp. 3-15.

Jarosevic, A. e Chandoga, M. 1994. Force Measuring of Prestressing Steel, Slovak Report on Prestressed Concrete 1990-1994, *XII International congress of FIP*. Washington, pp. 56-62.

LNEC, 1992. Dynamic Testing of the Guadiana Bridge" (in Portuguese), *Report*, Lisbon.

Magalhães, F. 2004. Stochastic Modal Identification for the Validation of Numerical Models, MSc. Thesis, FEUP, Porto (in Portuguese).

Pinto da Costa, A. ; Branco, F. & Martins, J. 1994. Analysis of the Cable Vibrations at the International Guadiana Bridge, *Proceedings of The International Conference on Cable-Stayed and Suspension Bridges*, AIPC-FIP, vol. 2 pp. 483-490, Deauville, France.