DYNAMIC TESTS ON A LARGE CABLE-STAYED BRIDGE AN EFFICIENT APPROACH

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ABSTRACT: This paper describes the dynamic tests performed on a large cable-stayed bridge, Vasco da Gama Bridge, on the basis of a non-conventional testing system, comprehending several independent accelerographs conveniently synchronised by a laptop, as well as a laser interferometry system for non-contact dynamic measurements in stay cables. This system showed to be rather portable, efficient and accurate, leading to the creation of a very large high quality data base concerning the dynamic behaviour of the bridge. Subsequent processing of the data permitted to identify accurately all the significant modal parameters of interest from the aerodynamic and seismic point of view, which present a very good correlation with the corresponding values provided by the 3-D numerical finite element model previously developed at the design stage.

INTRODUCTION

The development of reliable analytical dynamic models is a crucial aspect of major importance in terms of the study of the dynamic response and of the health condition of both new and existing large span bridges under traffic, wind or seismic loads. Although sophisticated finite element codes are currently available for that purpose, the success of their application is strongly dependent on the possibility of experimental verification of the results. An appropriate experimental calibration and validation of such analytical models, so that they can reflect correctly the structural properties and the boundary conditions, involves the experimental identification of the most significant modal parameters of the structure (natural frequencies, mode shapes and modal damping factors), and their correlation with the corresponding calculated values.

Dynamic tests for modal parameter identification on bridges can be generally classified according to the three following types: (i) forced vibration tests; (ii) ambient vibration tests and (iii) free vibration tests.

Forced vibration tests are directly related with the application of standard techniques of Experimental Modal Analysis (Ewins 1984), previously developed and applied in the context of

Mechanical, Aeronautic and Aerospace Engineering. They involve the application and measurement of single or multiple deterministic or random excitations, the simultaneous measurement of the structural response at several points, and the subsequent estimate of frequency response functions (FRFs). These FRFs are usually the basis for the application of multi-degree of freedom modal identification algorithms, that enable accurate estimates of the modal parameters, provided that the signal to noise ratio of the signals captured is high enough.

Impulse hammers and electrodynamic shakers are two types of equipment that can be used with success in forced vibration tests of relatively small structures like slabs or pedestrian bridges (Caetano and Cunha 1993). However, when dealing with large structures, much heavier and more expensive equipments are needed, like excentric mass or servo-hydraulic shakers (Pietrzko and Cantieni 1996). In case of large and flexible bridges, with significant natural frequencies in the range 0-1Hz, like cable-stayed or suspension bridges, it becomes still more difficult and costly to provide controlled excitation at enough high levels. As the magnitude of the force depends on the square value of the frequency of rotation, the application of sinusoidal shakers on very flexible structures requires very heavy equipments and involves important resources, related in particular with the transportation and mounting phases, as well as with the high power supply needed (Okauchi et al. 1997, Hoshino et al. 1997).

Ambient vibration tests are an interesting alternative, successfully applied to a large variety of civil engineering structures ranging from short to long span bridges, high-rise buildings and dams. This method only requires the measurement of the structural response under ambient excitation, usually due to wind or traffic, and can lead to accurate estimates of the modal parameters quickly and inexpensively. Furthermore, it can provide the benefit of avoiding shut down vehicle traffic during the tests due to the installation of heavy shakers. The usual testing procedure consists of performing several measurements simultaneously at one or more reference points and at different other points along the structure. Assuming that the excitation is relatively smoothly distributed in the frequency band of interest, it is easy to obtain, in the frequency domain, amplitude and phase relations between the structural response at the several points of measurement, which can lead to accurate estimates of natural frequencies and mode shapes (Felber 1993).

Though modal damping factors can be also identified using ambient vibration tests, the corresponding estimates are often not so accurate, and this may be a major point of concern in some applications. This is the case of large cable-stayed or suspension bridges, whose analysis and design implies a detailed study of the conditions of flutter aerodynamic instability (Jones et al. 1998), in which the structural damping plays a crucial role. It is therefore particularly appropriate in such cases to perform a free vibration test, introducing an initial perturbation that can induce a free vibration response significantly higher than the ambient response. This can be done using a tensioned cable anchored to the soil, with a fusible connection, and increasing the corresponding tension till the limit (Ventura et al. 1996), or alternatively provoking a sudden release of a mass appropriately suspended from the deck (Delgado et al. 1998)

The conventional hardware which forms a typical ambient or free vibration bridge testing system is described in Figure 1, and comprehends (Felber 1997): (i) a set of sensors, commonly forced balanced accelerometers permitting to reliably sense accelerations as small as $1\mu g$; (ii) amplifier and filter units, covering high gains and providing selectable low-pass filtering with low cut-off frequencies to remove all unwanted higher frequencies from the signals; (iii) an analog to digital converter capable of digitizing the analog signals with a minimum of 16 bit resolution, conveniently controlled by software so as to permit the acquisition of very long records; (iv) one computer coordinating the data acquisition and eventually a second one to perform all on site data analysis, mode shape animation and printing.

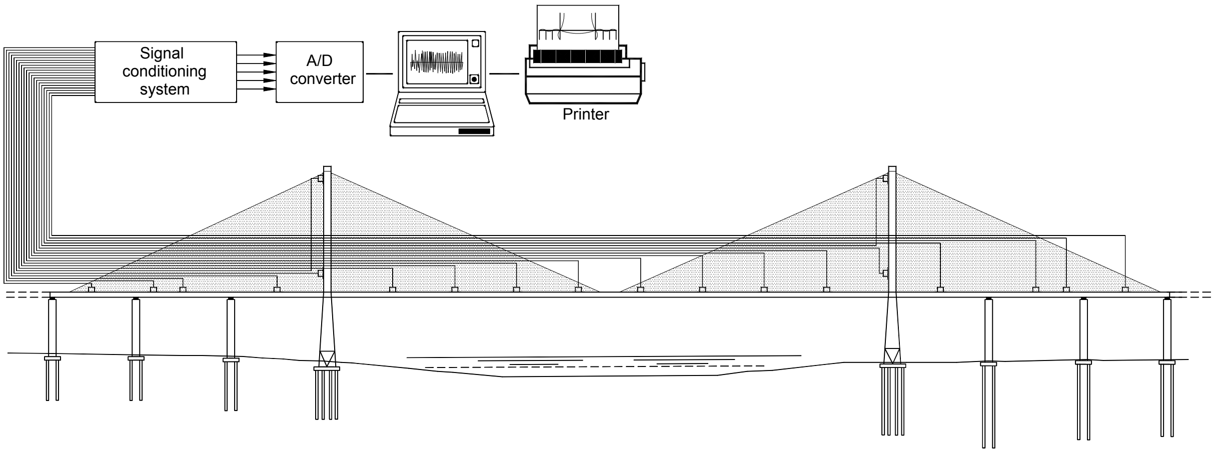


FIG. 1: Schematic of a conventional ambient vibration testing system

Although such conventional ambient vibration systems have been used with success (Brownjohn et al. 1989; Felber and Cantieni 1996), they present a strong drawback related with some lack of portability and with the necessity of developing a rather hard and tedious setup, using many hundreds of meters of electric cables, which should be tough, shielded and ensure a minimal signal loss and interference over large distances. Beyond that, in the specific case of cable-stayed bridges, in which the performance of systematic dynamic measurements on stay cables can be worth for several reasons (Cunha and Caetano 1999), the instrumentation based on conventional accelerometers can be also rather boring.

The present paper describes in detail the dynamic tests recently performed on a large cable-stayed bridge, Vasco da Gama Bridge, using a non-conventional testing system. This system, comprehending several independent accelerographs conveniently synchronised, as well as a laser interferometry system for non-contact dynamic measurements in stay cables, revealed to be rather portable, efficient and accurate, leading to the creation of a very large high quality data base concerning the dynamic behaviour of the bridge. Subsequent processing of the data permitted to identify accurately all the significant modal parameters of interest from the aerodynamic and seismic point of view, which show a very good correlation with the corresponding values provided by the 3-D numerical finite element model previously developed at the design stage.

THE VASCO DA GAMA CABLE-STAYED BRIDGE

FIG. 2: View of Vasco da Gama cable-stayed bridge

The Vasco da Gama Bridge is the new Tagus River crossing in Portugal, 17300m long, including three interchanges, a 5km long section on land and a continuous 12300m long bridge. The Bridge was recently constructed close to the area of EXPO-98 international exhibition, and includes a cable-stayed component (Figure 2) over the main navigation channel with 420m central span and three lateral spans (62+70.6+72m) on each side, corresponding to a total length of 829.2m between transition piers. The deck is 31m wide and is formed by two lateral prestressed girders, 2.6m high, connected by a slab and by transverse steel I girders. It is continuous along its total length and it is suspended at level 52.5m by two plans of 48 stays connected to each tower. The two H shaped towers are 147m high above a massive zone at their base designed for protection against ship collision.

OBJECTIVES AND TASKS OF THE DYNAMIC TESTS

Due to the high proneness of long span bridges to aerodynamic instability problems, as well as to the high seismic risk of the Southern part of Portugal, the dynamic behaviour of Vasco da Gama cable-stayed bridge has been extensively studied using both experimental and numerical approaches (Grillaud et al. 1997; Branco et al. 1998). In particular, dynamic tests have been performed by the University of Porto (Delgado et al. 1998) in order to experimentally identify the most relevant modal parameters of the cable-stayed bridge from the aerodynamic and seismic behaviour point of view, and correlate them with the corresponding parameters provided by the 3-D numerical model developed by EEG (Europe Études Gecti, Villeurbanne, France), using the finite element program Hercules.

The dynamic tests involved: (i) preliminary measurements for evaluation of the levels of acceleration and identification of an appropriate reference section; (ii) an ambient vibration test to identify global natural frequencies and mode shapes of the bridge, measuring the structural response at 58 different points along the deck and towers; (iii) the performance of response measurements during the passage of heavy trucks, passing over a hood plank, to increase the vertical accelerations; (iv) a free vibration test, based on the sudden release of a 60t mass excentrically suspended from the deck, in order to accurately identify modal damping factors; (v) dynamic measurements on stay cables in order to identify either global natural frequencies of the whole structure or local frequencies of the stay cables, both using conventional piezoelectric accelerometers and an interferometry laser sensor; (vi) experimental evaluation of dynamic amplification factors (DAFs) associated to the passage of heavy traffic at different speeds and along several lanes.

AMBIENT VIBRATION TEST

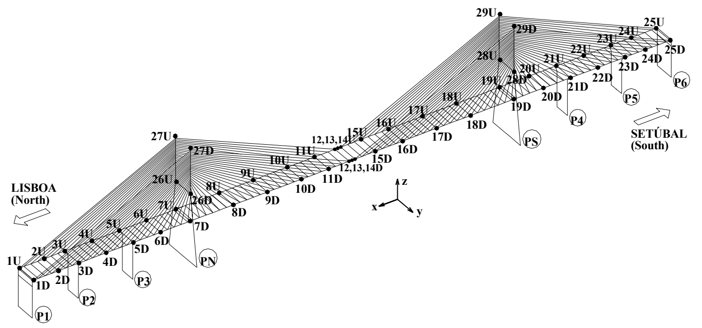


FIG. 3: Schematic representation of the bridge with indication of the measurement sections used in the ambient vibration test

The ambient vibration test was developed performing vibration measurements with six independent triaxial accelerographs, two of them being permanently installed at a given reference cross section (section 10, 1/3 span North), while the others were successively placed at 28 different mobile sections along the deck and towers (Figure 3). In all sections, the pairs of sensors were located laterally, upstream and downstream, always oriented according to the orthogonal referential *xx* (longitudinal direction), *yy* (transversal) and *zz* (vertical). These accelerographs were appropriately programmed before each sequence of measurements, in order to begin the acquisition simultaneously every twenty minutes, in principle. Taking into account the very low frequency range of interest (0-1Hz), the time of acquisition for each setup was always 16 minutes, with a sampling frequency of 50Hz, so as to obtain average spectral estimates with a frequency resolution inferior to 0.01Hz. The time left to change the position of the accelerographs between successive setups was of 4 minutes, except in the case of measurements along the towers, due to the necessity of climbing the stairs till the top, transporting the accelerographs in rock-bags. Due to the relatively low level of signal captured, appropriate amplification factors were used, leading to a precision superior to 0.015mg ($1g/2^{16}$), in consequence of the use of 16 bit A/D converters. With the purpose of increasing the signal level in the vertical component, vibration measurements were also carried out during the passage of a heavy truck, with a mass of 30t, over a hood plank, 4cm high, placed at 1/3 span. It is worth emphasizing that the measurement system used revealed to be quite practical and efficient, permitting the development of the whole ambient vibration test in 2.5 days, avoiding completely the necessity of using long electric cables connecting the 18 force balanced accelerometers to a conventional central data acquisition and processing system. The experimental data obtained was periodically downloaded to the hard disk of a laptop and subsequently analysed and processed in order to extract global modal parameters of the bridge. It is noteworthy that, although most of the signal processing and modal identification work has been developed in the lab, it could have been even performed in the field during the tests, provided that appropriate software for only output system identification and mode animation had been previously installed in the laptop. Beyond this measurement system, an anemometer was still used to regularly measure the wind speed. Inspection of the time records obtained showed a significant variation of the structural response during the ambient vibration test, which was essentially due to oscillations of the wind speed. The average wind speed measured at midspan varied between 1 and 22m/s, leading to a considerable oscillation of the r.m.s. values of acceleration at the reference section (in the range 0.06 to 1.69mg in the vertical direction, 0.03 to 0.35mg in the transversal direction and 0.03 to 0.13mg in the longitudinal direction).

The identification of natural frequencies was based on the peak values of averages of normalised acceleration power spectra (NPSD) corresponding to each section (downstream, upstream, half-sum and half-difference signals), as well as on the coherence values associated to the simultaneous measurements at the several pairs of points (Felber 1993). The frequency resolution of the average spectral estimates obtained, on the basis of time records of 16 minutes, was 0.006Hz. Figure 4 shows average normalised auto spectra (ANPSD) and cross-spectra (ANCPSD), corresponding to vertical (Z) and transversal (Y) acceleration components, obtained as average of NPSD and NCPSD spectra associated to the measurement in 23 different sections, taking into account both the half-sum and the half-difference signals (upstream-downstream). Figure 5 also shows the amplitudes of NCPSD spectra and the corresponding coherence functions associated to simultaneous measurements at sections 10 and 16. Inspection of all the average spectral estimates obtained (Delgado et al. 1998) permitted to identify the values of natural frequencies summarised in Table 1, in the range 0-1.15Hz, in correspondence with natural frequencies provided by the numerical model.

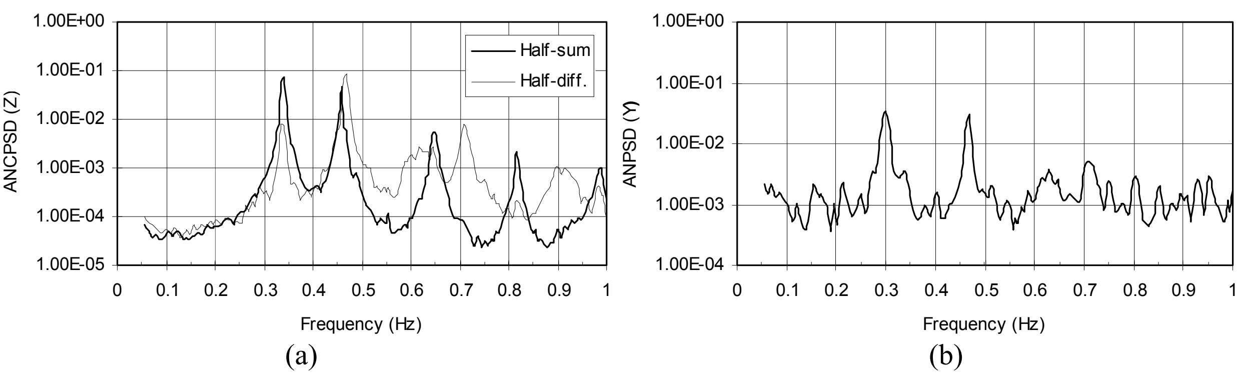
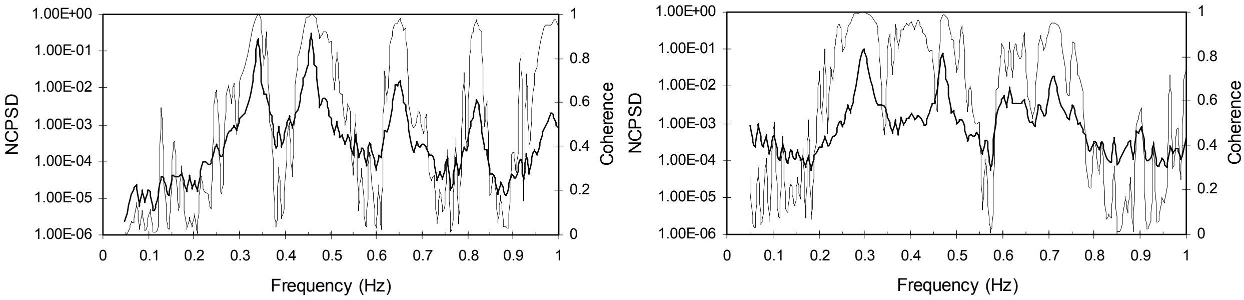


FIG. 4. Average normalised spectra associated to: (a) vertical acceleration (half-sum and half-difference signals, upstream-downstream); (b) transversal acceleration (half-sum signal)



(a) (b)

FIG. 5. NCPSD spectra (amplitude) of the half-sum signal of (a) vertical acceleration and of (b) transversal acceleration at sections 10 and 16, and corresponding coherences

The identification of modes of vibration with frequencies in the range 0-1.15Hz was based on the estimates of transfer functions (using estimator H_1), and corresponding coherences, relating the ambient response at the reference section (half-sum and half-difference signals, upstream-downstream) with the response at the other measurement sections along the deck and towers. The ratios between the values of those transfer functions related to each natural frequency (linear magnitude) associated to the several sections led to the absolute value of the modal components, the corresponding signal having been evaluated on the basis of the phase evolution. Figure 6 shows some of the identified modal shapes of the deck, also presenting the corresponding numerical modes, as well as some modal components identified using the free vibration test, described in the next section.

TABLE 1. Identified and calculated natural frequencies

Calculated frequencies (Hz)	Identified frequencies (Hz)	Type of mode of vibration
0.2624	0.298	1^{st} transversal bending
0.3185	0.341	1^{st} vertical bending
0.4287	0.437	2^{nd} vertical bending
0.4386	0.471	1^{st} torsion + transversal bending
0.6268	0.572*/0.590*/0.599*/0.619*/0.624*	2^{nd} torsion + transversal bending
0.6077	0.651	3^{rd} vertical bending
0.6268	0.693*/0.707*/0.718*/0.755*	2^{nd} torsion + transversal bending
0.7600	0.817*	4^{th} vertical bending
(**)	0.895*/0.917*	3^{rd} torsion
(**)	0.985	5^{th} vertical bending
(**)	1.129*	4^{th} vertical bending

(*) – multiple modes, low signal level

(**) - uknown

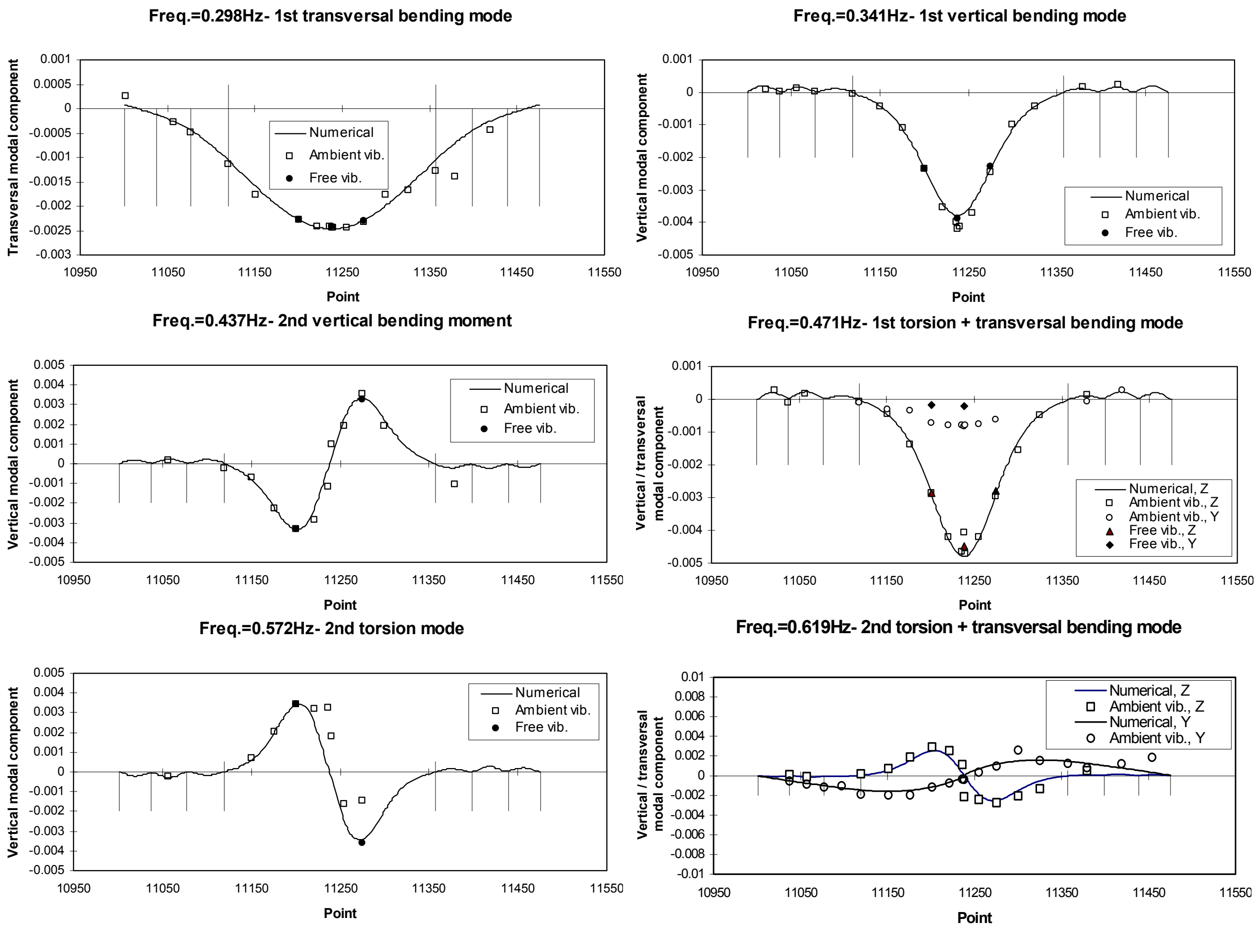


FIG. 6(a). Some modal shapes of the deck

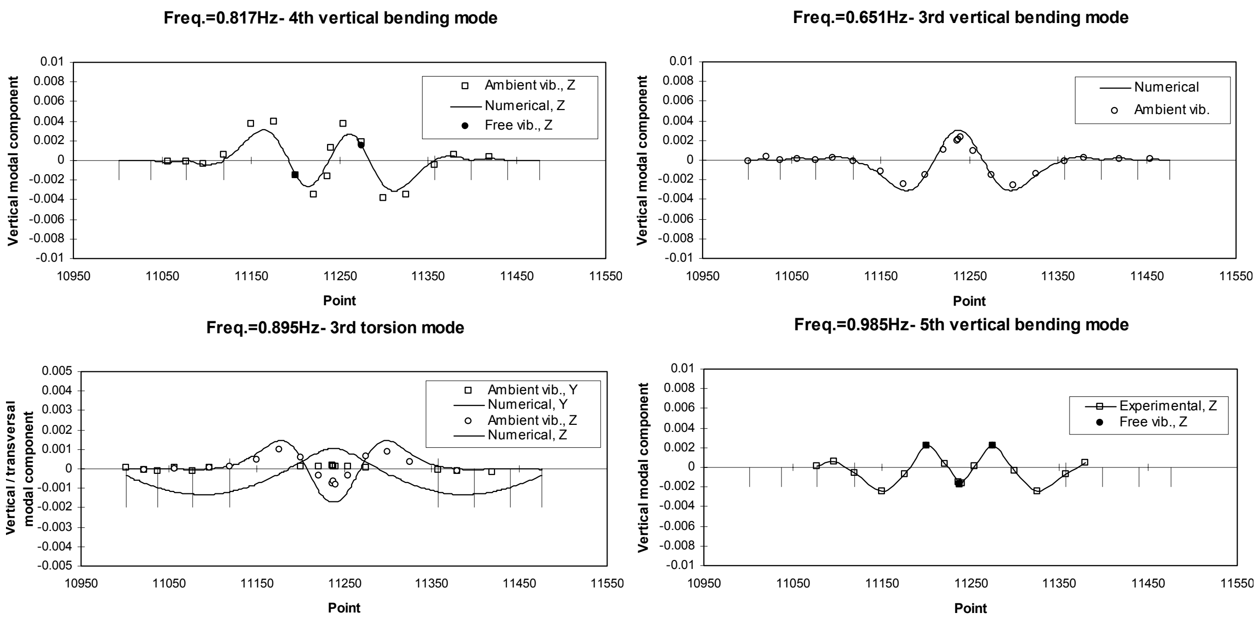


FIG. 6(b): Some modal shapes of the deck

FREE VIBRATION TEST

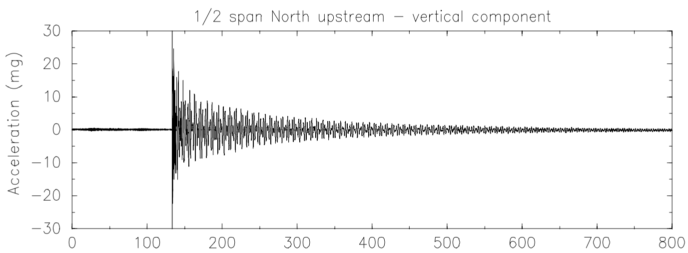

(a)


(b)


(c)

FIG. 7: Free vibration test: (a) Excentrically suspended 60t barge; (b) Starting cut of hanging Dywidag bar; (c) Release of barge

The free vibration test was performed not only to check the main results of the ambient vibration test previously developed, but essentially to permit an accurate identification of the damping factors associated with the modes of vibration with a more significant contribution to the dynamic response of the bridge, particularly under wind loading. For that purpose, a mass of 60t was suspended from one point of the deck close to the section 1/3 span North (Figure 7), near the upstream border, and was subsequently released, originating a vibratory phenomenon recorded during 16 minutes by 6 triaxial accelerographs, located at the sections 1/3 and 1/2 span (upstream and downstream). In order to verify that the wind would not affect the accuracy of evaluation of the structural modal damping factors, introducing a component of aerodynamic damping, the wind speed was permanently measured at midspan, connecting the anemometer to a spectral analyzer, the maximum wind velocity not exceeding 2.5m/s.



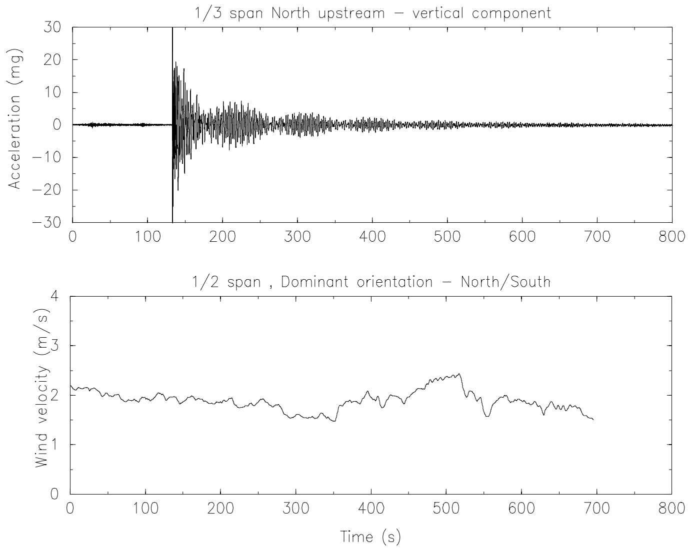
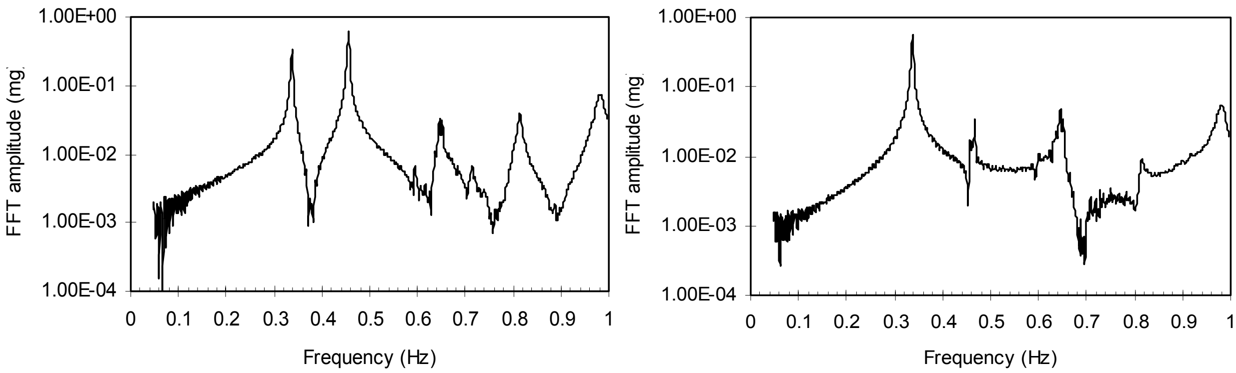


FIG. 8. Vertical component of acceleration at 1/2 span (upstream) and at 1/3 span North (upstream) and temporal evolution of the wind speed at 1/2 span (upstream)

The identification of natural frequencies was then made on the basis of the peaks of the FFTs of the acceleration time series (Figures 9-10). Each one of these series (Figure 8) was formed by 32768 points sampled at 50Hz, corresponding to a time of acquisition of 655.36s, which led to a frequency resolution of 0.0015Hz.

With regard to the mode shapes, these were identified applying a band-pass 10 poles Butterworth digital filter around each of the natural frequencies identified, and comparing the amplitudes and phases of the filtered signals at different points of measurement. Figure 6 shows the modal components identified by this procedure, which are clearly in good agreement both with the mode shapes obtained by the ambient vibration test and with the modal configurations calculated numerically.



(a) (b)

FIG. 9. Amplitude of the FFT of the half-sum signal of vertical acceleration (upstream-downstream) at (a) 1/3 span North and (b) 1/2 span

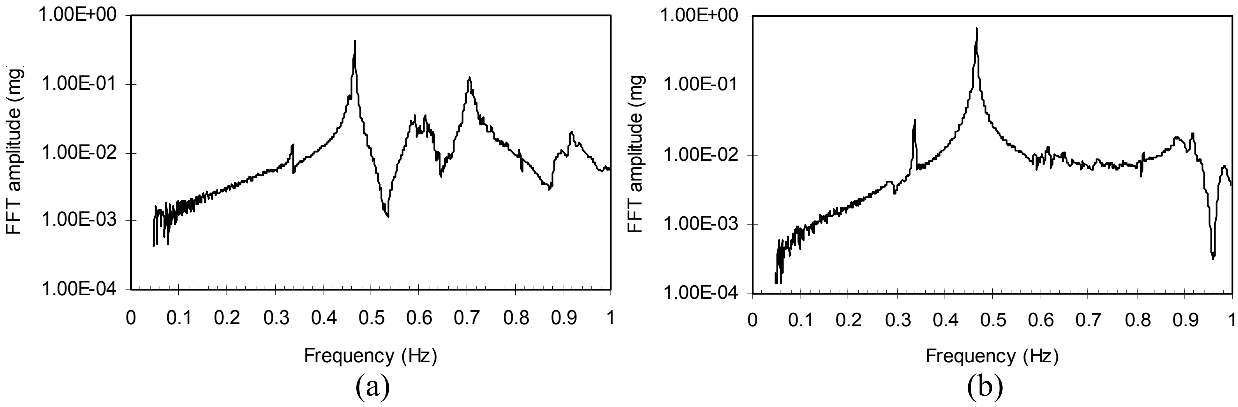


FIG. 10. Amplitude of the FFT of the half-difference signal of vertical acceleration (upstream-downstream) at (a) 1/3 span North and (b) 1/2 span

At last, the identification of the modal damping factors was done on the basis of the decay of the envelope of the filtered signals obtained applying also a band-pass 10 poles Butterworth digital filter around each natural frequency in the range 0-1.0Hz (Figure 11). As the estimates of the modal damping factors depend on the level of vibration, different exponential regressions were performed in correspondence with different time intervals of the free response. Table 2 shows the average estimates obtained, as well as the respective intervals of variation.

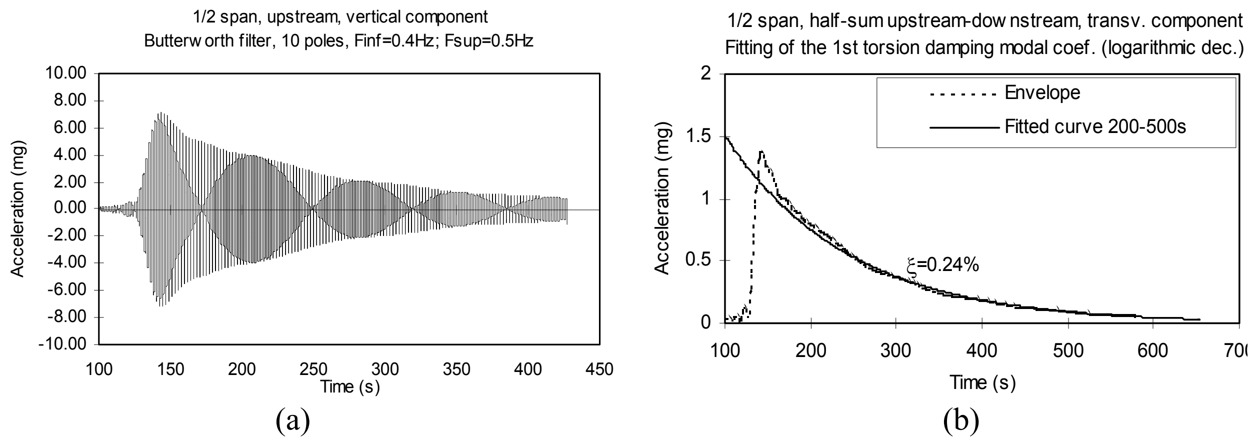


FIG. 11. Identification of the modal damping factor associated with the natural frequency 0.467Hz. Analysis based on the measured response at 1/2 span upstream

TABLE 2. Identified natural frequencies and modal damping factors

Identified natural frequency (Hz)	Modal damping factor (%)		Type of mode
	Mean value	Int. of variation	
0.295	1.23	0.87-1.73	1st transversal bending
0.338	0.21	0.16-0.40	1st vertical bending
0.456	0.23	0.19-0.27	2nd vertical bending
0.467	0.24	0.14-0.36	1st torsion + transversal bending
0.591	0.34	0.30-0.39	2nd torsion + transversal bending
0.647*	0.37		3rd vertical bending
0.653*	0.20		
0.707	0.78	0.71-1.12	2nd torsion + transversal bending
0.814	0.48	0.45-0.54	4th vertical bending
0.982	0.74	0.67-1.24	5th vertical bending

(*) – Multiple modes; identification based on the half-power bandwidth method due to the difficulty of application of digital filters

It is worth mentioning that, beyond the application of the logarithmic decrement method, the frequency domain MDOF identification algorithm RFP (Rational Fraction Polynomial Method (Han and Wicks 1989)) was still used, based on transfer functions relating the response measured at each point with the excitation. As the excitation was not actually measured when the mass of 60t was suddenly released from the deck, the transfer functions were evaluated assuming the input as an impulsive load, with unit magnitude, applied during a very short period of time, leading to a spectral content of the excitation with an almost constant intensity over the frequency range of interest. Figure 12 shows two of the transfer functions obtained following this procedure, as well as the corresponding synthesised transfer functions, evaluated on the basis of the modal parameters identified using the RFP algorithm.

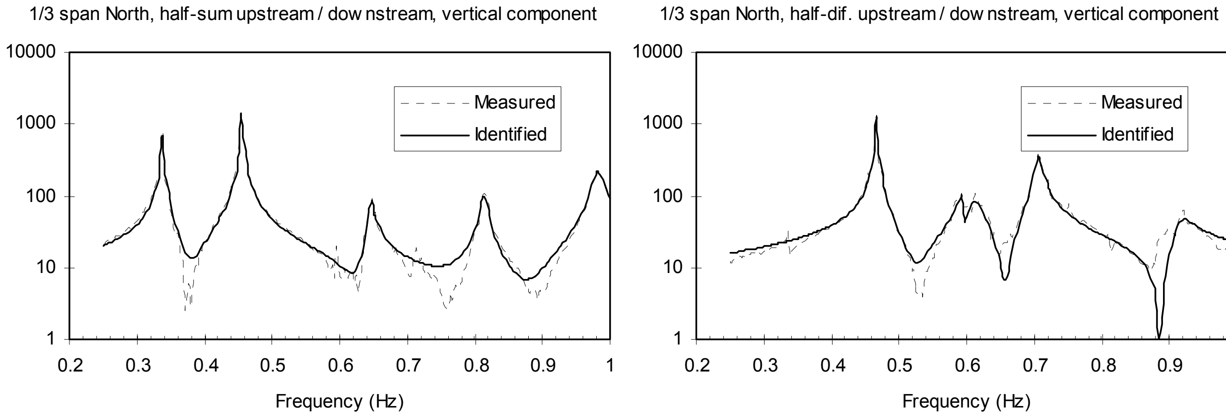


FIG. 12. Identification of modal parameters using the RFP method. Measured and synthesised transfer functions.

DYNAMIC MEASUREMENTS ON STAY CABLES

Objective of the measurements

Dynamic measurements on stay cables are often required to assess different problems of great interest in the context of the design, construction and maintenance of cable-stayed bridges, such as: (i) The evaluation of cable tensions, whose knowledge is critical to the correct alignment and distribution of internal forces in the finished bridge, and whose change in time can provide interesting indications concerning the structural health; (ii) The evaluation of damping characteristics of damping devices installed close to the cable anchorages (iii) The assessment of fatigue problems in stay cables caused by long-term traffic loads; (iv) The evaluation of the level of importance of cable vibrations, that can occur due to vortex-shedding phenomena, parametric or rain-wind excitation, and that have affected the behaviour of several important cable-stayed bridges, like Faroe, Helgeland, Ben-Ahin, Wandre (Cremer et al. 1995), Second Severn Crossing or Erasmus bridges (Geurts et al. 1998); (v) The experimental identification of local and global natural frequencies, which may contribute to validate and update finite element numerical models used to simulate the dynamic behaviour of the bridge under wind or seismic loads.

The most common way of making such dynamic measurements is based on the use of accelerometers conveniently attached to the external cable surface, which involves a rather hard and tedious setup when dealing with the large number of stay cables, common in modern cable-stayed bridges. Therefore, in terms of practical applications, it is of utmost importance to develop and apply new measurement systems that enable systematic and accurate dynamic measurements on stay cables in a simple and comfortable way.

Under these circumstances, some measurements of vibrations in some of the longest cables of Vasco da Gama cable-stayed bridge were also developed on the basis of a laser Doppler velocimeter, in order to clarify the reliability and practical interest of this alternative measurement technique, which presents the remarkable advantage of avoiding the direct contact with the structure. The dynamic measurements on stay cables were carried out simultaneously with piezoelectric accelerometers. The results obtained showed clearly that the use of this laser system provided an excellent accuracy in comparison with conventional accelerometers. Furthermore an enormous simplicity in terms of practical application could be also verified.

Identification of natural frequencies

For the purpose of measuring vibrations in some of the longest stay cables, the accelerometers were screwed on small metallic cubes, conveniently attached to the external surface of the stay cables with the help of metallic belts strongly tightened. This relatively boring preparatory operation, only possible as the bridge was not open to the normal road traffic yet, was systematically repeated in all the stay cables observed, placing the accelerometers 5m above the deck by means of a crane, and measuring vibrations in the vertical plane (Figures 13,14(a)). The use of the laser transducer became however incomparably easier, the only operation needed being the control of the position of the laser head, simply placed on the deck under each cable, in order to produce a laser beam hitting the cable surface at the section of application of the corresponding accelerometer (Figure 14(b)). Due to the significant inclination of the cables observed, the laser beam could be positioned vertically, and the output signal of the laser sensor was directly connected with a spectral analyzer. No special targets were used for the laser beam, in order to improve the signal to noise ratio. It is still worth noting that, although a distance of observation of 5m has been used to permit a correct comparison of results with the accelerometer, larger distances of observation of the laser sensor, of the order of several tenths of meters, can be used without considerable loss of accuracy, as previously shown by Cunha et al (Cunha et al. 1995).

FIG. 13. Installation of accelerometers on stay cables

(a) (b)

FIG. 14. (a) Measurement of vibrations in a stay-cable using an accelerometer; (b) Laser head placed on the deck surface hitting a stay-cable with a vertical laser beam (at night)

Figure 15 presents a direct comparison between the acceleration average power spectra associated to the ambient response of one of the longest stay cables of the bridge, obtained with simultaneous measurements at the same point on the basis of the two types of sensors mentioned, averaging over 16 records, using a frequency resolution of 0.0078Hz and performing a digital differentiation of the laser velocity signal, using a FFT algorithm. This comparison shows the excellent agreement achieved in terms of the identification of the local natural frequencies of the cable, characterised by equally spaced well pronounced peaks, and the lower noise level of the laser system. Moreover, some global natural frequencies of the bridge, corresponding to main peaks of the spectra in the range 0-1Hz, are also apparent, though not so clearly in the case of the laser sensor, as this transducer measures the relative velocity between the deck and the stay cable. The same conclusion can also be drawn when comparing the natural frequencies identified using the laser sensor with those obtained with conventional equipment in the free vibration test (Figure 16). In this last case, the peaks related to global natural frequencies are still more evident, due to the much higher level of global vibrations recorded during the free vibration test.

The values of the first 5 natural frequencies of the stay cable observed, identified on the basis of these spectra using the two measurement systems referred, are virtually coincident (0.594, 1.180, 1.766, 2.367, 2.953Hz), the only difference noted in one of the natural frequencies being equal to the frequency resolution (0.0078Hz).

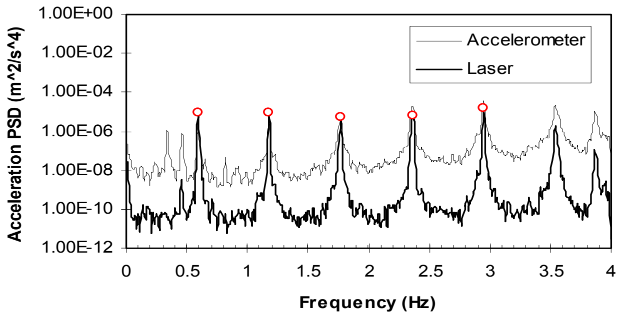


FIG. 15. Comparison of acceleration average power spectra of the ambient response of a stay cable

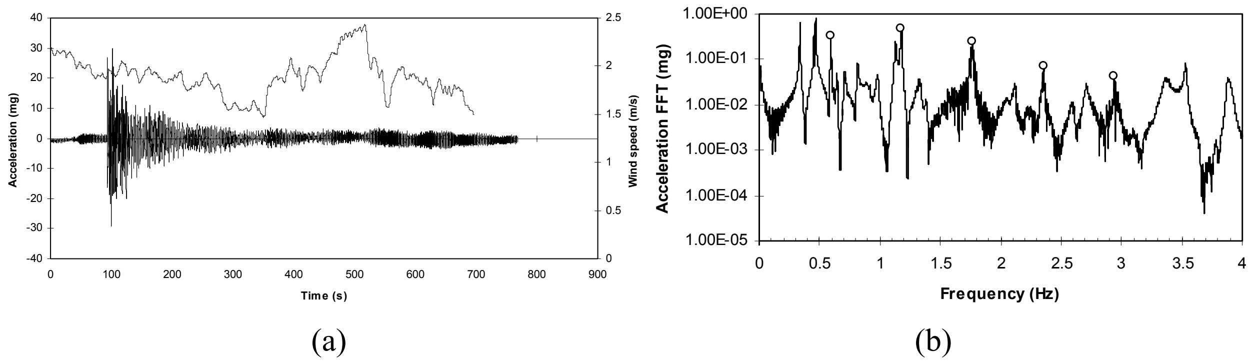


FIG. 16. Response of the stay cable during the free vibration test of the bridge: (a) Cable response and wind speed at 1/2 span; (b) FFT of the cable response

Evaluation of cable tensions

Several techniques can be employed to evaluate cable forces, namely measurement of the force in a tensioning jack, application of a ring load-cell, topographic measurements, elongation of the cables during tension and installation of strain gauges in the strands. As referred by Casas (Casas 1994), in spite of their simple theoretical bases, each of these methods is complex in its practical application and, in some cases, the level of accuracy is insufficient.

A relatively simpler and less expensive method to estimate cable tensions in cable-stayed bridges is based on the vibrating chord theory, taking into consideration the identified values of natural frequencies of the stay cables, which leads to the following relation:

$$T = \frac{4mf_n^2 L^2}{n^2} \qquad (1)$$

where T is the cable tension, f_n is the n-th natural frequency, L is the distance between fixed cable ends and m represents the mass of the cable per unit length. Application of this approach, taking $L = 214.97m$, $m = 96.9kg/m$ and considering the identified values of the first 5 natural frequencies of the cable, leads to an average value of the cable tension of 6256kN, using the accelerometer, and 6266kN, using the laser sensor.

CONCLUSIONS

The development of the dynamic tests described in this paper permitted to extract the following main conclusions:

- The measurement system used in the ambient and free vibration tests, based on the use of independent triaxial accelerographs conveniently programmed and synchronised by a laptop, revealed to be a very efficient and comfortable solution, avoiding the use of several hundred meters of electric cables and permitting the integral data acquisition within a relatively short period of time;
- The ambient vibration test provided a very accurate estimate of natural frequencies and mode shapes, despite the rather low level of signal captured (between 0.36 and 12.5mg of maximum vertical acceleration at the reference section in the several records), the low range of natural frequencies of interest (0-1Hz) and the relatively high number of modes of vibration in that range;
- The free vibration test, based on the sudden release of a 60t mass suspended from the deck, seemed to be quite useful as a complementary test that permitted not only to check the previous identification of natural frequencies and mode shapes, but essentially the very accurate identification of modal damping factors, whose knowledge is particularly relevant in terms of the study of the aerodynamic stability of the bridge;
- There is, in general, a very good correlation between modal parameters identified and the corresponding parameters calculated on the basis of the 3D finite element model developed at the design stage, though some small differences can be found, as it is the case of the multiple modes identified associated to the 2^{nd} torsion + transversal bending numerical mode, related with local stay cable frequencies, or of the 3^{rd} torsion mode, in which no transversal bending component was experimentally detected;
- Although no force measurement has been performed during the free vibration test, a standard MDOF identification algorithm (RFP – Rational Fraction Polynomial method) in the frequency domain could be applied with success, assuming the input as an impulsive load, with unit magnitude, acting during a very short period of time, leading to a spectral content of the excitation with an almost constant intensity over the frequency range of interest;
- The application of a laser Doppler velocity transducer revealed to be a rather accurate and easy to use non-contact vibration measurement technique, particularly appropriate to perform dynamic measurements in stay cables of cable-stayed bridges, providing a powerful form of systematic and

accurate evaluation of natural frequencies and cable tensions, which is a factor of significant importance, in particular, in terms of the long term health monitoring of this type of bridges.

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