VIBRATION ANALYSIS AND MODAL IDENTIFICATION OF A CIRCULAR CABLE-STAYED FOOTBRIDGE

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Abstract

Vibration measurements and modal identification were performed on a footbridge as part of the commissioning tests. The deck presents a circular configuration, in plant, and is suspended from eight cables connecting it to the extremity of a steel mast anchored to a concrete bulk situated on the riverside. The dynamic measurements were aimed to control the force installed in the cables during the tension operation and to characterize the dynamic parameters through output-only modal identification techniques in order to calibrate a Finite Element model. At last, groups of pedestrians crossed the bridge at various speeds allowing conclusions about the vibration amplitudes that can be expected during real use of the bridge.

1 Introduction

Recently a number of footbridges were built in Portugal in the scope of the urban renovation plans of several cities. This paper deals with the modal identification and vibration measurements of one of these structures located in Aveiro, Portugal.

The circular configuration in plant of the bridge allows the link between three points located on the banks of the T-shape junction of two canals (see figures 1 and 2).

The vibration measurements are part of the on-site structural characterization of the bridge that also included load tests with photogrametric survey and long-term strain measurements using Brag sensors located on the cables and on the mast.

Before performing the vibrations measurements for the modal identification it was necessary to control the introduction of the correct forces in the stay-cables. The dynamic measurements were aimed to control the force installed in the cables during the tension operation, considering that the natural frequency of the cables is directly related to the value of the installed tension. Thus, to adjust the value of the force, the first natural frequency of the eight cables was monitored simultaneously during the operation.

The main objective was the characterization of the dynamic parameters through output-only modal identification techniques in order to calibrate a Finite Element model. A total of fourteen measurement points were established along the bridge deck. The data acquisition was performed using four free and four fixed accelerometers, including one fixed measurement degree of freedom at the top of the mast. The modal extraction was made using the ARTeMIS software. The calibration of the FE model was made using six natural modes and frequencies. A good correspondence was achieved for each of them. The difficulty in the exact modelling of the real boundary conditions at some points along the deck led to lower MAC values for the higher modes.

Figure 1 – Localization of the bridge

Figure 2 – Circular Footbridge

At the end, groups of pedestrians crossed the bridge at speeds from approximately 1.8 to 3.5 steps/second, to obtain acceleration response histories to be compared with numerical results. These measurements allowed conclusions about the dynamic loads and vibration amplitudes that can be expected during real use of the bridge

2 Bridge description

The Footbridge presents a circular configuration, in plant, and the deck is suspended from eight cables connecting it to the extremity of a steel mast anchored to a concrete bulk situated on the riverside.

Figure 3 – Side view of tower, stay-strips and stay- cables

Figure 4 – Top of the tower

The deck is a 2 meters wide wooden floor with a circular configuration in plant corresponding to a circle with 13 meters radius. This is supported by a structure constituted by 55 modules made of steel profiles. The longitudinal profiles are HEB200 and the radial and diagonal profiles are HEB100. Each module is approximately 1.5 meters long. The whole deck can be considered structurally as a truss, very stiff in its own horizontal plane, supported by the cables and on three points located on the banks.

The bow shaped tower is a pipe with a quadrangular tapered steel welded cross-section. The section width varies from 0.60 meter, near the fixed supports, to 0.43 meter, at the top. The section height is constant and equal to 0.43 meter.

The tower is stabilized by two steel strips anchored behind the tower (see figure 3). The stay cables are anchored at the top of the tower (see figure 4). The section of each steel strip has a rectangular form with 500x15 mm^2 and the cables are made of cylindrical steel bars with 36 mm diameter, being the corresponding lengths given in table 1, with reference to figure 5-a.

Table 1 – Stay-cables length

Cable number	1	2	3	4	5	6	7	8
Cable Length (mm)	6139	6743	7617	8607	8625	7670	6828	6210

3 Tests and measurements

The vibration monitoring of the bridge was planned according to the following objectives:

1. to assure the correct installation of axial forces in the cables;
2. to characterize the dynamic behaviour of the bridge; and
3. to measure the dynamic response when groups of synchronized pedestrians cross the bridge.

3.1 Stay-cable forces

The planned structural behaviour of the bridge deck depends on the correct forces installed in the cables. Therefore, it was necessary to assure that these forces correspond to those predicted by the designer.

A simple procedure to control the cable forces can be carried out if the natural frequencies of the cables are monitored during prestressing. This was done using eight measurement channels and a frequency analyser to estimate the natural frequencies simultaneously in all cables. The cable force could be easily changed by means of a screw system available in the cable.

The natural frequency (f_n) corresponding to the n^{th} mode of vibration of a tensioned cable can be obtained from a simple equation relating the axial force (T) to the mass per unit length (m); the cable length (L); and to the natural frequency in Hz:

$$f_n^2 = \frac{Tn^2}{4mL^2} \tag{1}$$

Actually, the precision of this expression, based on the theory of vibrating strings, depends on the number n of the frequency that is being evaluated. For the first frequency the precision is usually lower than for the higher frequencies.

The parameter

$$\lambda^2 = (9{,}8mL)^2 \frac{EA}{T^3} \tag{2}$$

is a measure of the geometric characteristics and of the deformability of this type of cables. Values of λ^2 lower than 1 usually indicate that the error in equation (1) is very low. The higher the stress in the cable, the more precise is that expression. For the cables used in the bridge (see table 1 and figure 5-a) the values vary from about 0.5 for cables 1 and 8 to about 1.4 for cables 2 and 7. All the other cables present values lower than 1.

In the present case the first frequency obtained from equation (1) gives results with enough precision and therefore it was used to estimate the tension force. The reason why the first natural frequency was used instead of a higher frequency is that some construction works were still being performed at the time the measurements were made, introducing some noise in the acquired data. It was observed that, under these circumstances, the first frequency was the best choice.

After several iterations concerning the force introduced in each cable, the results given in table 2 were obtained. A sufficiently good approximation between measured values and those predicted by the designer was observed.

Table 2 – Stay-cables axial forces for dead loads

Cable number	1	2	3	4	5	6	7	8
1st Frequency [Hz]	2.75	2.24	2.20	2.24	2.28	2.25	2.24	2.81
Axial Force (eq. 1) [kN]	44.31	34.66	41.77	54.07	56.07	43.97	35.07	46.75
Design force [kN]	44.50	32.00	44.00	57.50	57.50	44.00	32.00	44.50

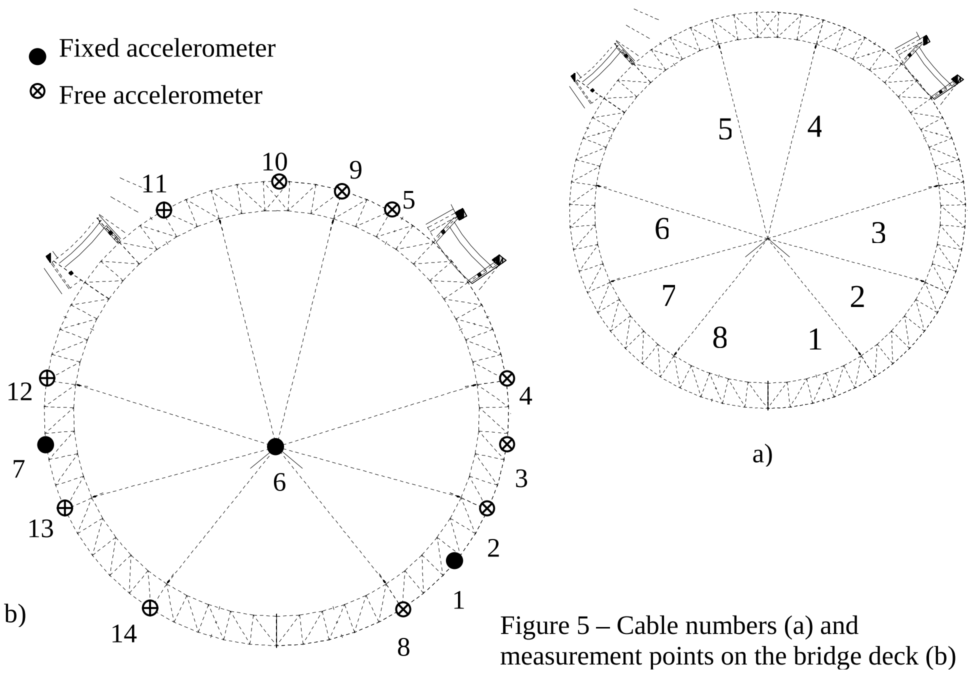

Figure 5 – Cable numbers (a) and measurement points on the bridge deck (b)

3.2 *Modal identification*

The modal identification was based on the techniques of modal extraction in the frequency domain implemented in ARTeMIS software, namely the frequency domain decomposition and the stochastic subspace iteration methods. These techniques allow the estimation not only of modal damping and natural frequencies, but also of the modal shapes of the deck.

The vertical acceleration induced by the ambient excitation mainly from wind loads was measured on the bridge deck and on the top of the mast. To assure a sufficient definition of the modal shapes fourteen measurement points were considered (see figure 5-b), three of them with fixed accelerometers (points 1, 6 and 7) and the remaining eleven with free accelerometers. A total of three setups with 10 minutes duration each were enough to obtain the ambient vibration response at each measurement point necessary to identify the modal parameters.

The results of the experimental modal analysis are summarized in figure 6 and in table 3. The natural frequencies of the steel strips behind the mast appear very clearly in the range 1.7 to 1.85Hz. Since eq (1) is a good approximation also for the natural frequencies of these strips, it was possible to calculate the corresponding tension forces using these frequencies and to verify that these correspond to the values predicted by the designer. The values are not exactly the same because the structure is not perfectly symmetrical in plant.

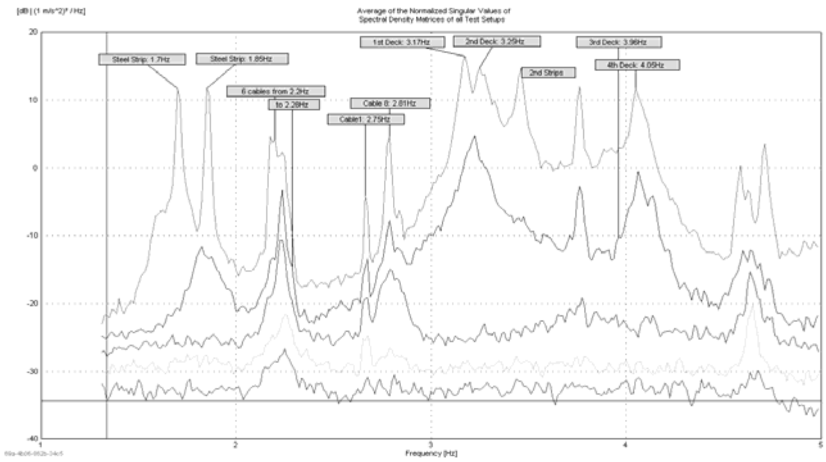

Figure 6 – Peak-picking and correpondence with the natural frequencies of the structural elements

Table 3: Natural frequencies and damping

Frequency [Hz]	Damping [%]	Frequency in the numerical model [Hz]	Mode identification
1.70	1.9		Steel strip supporting the mast
1.85	0.2		Steel strip supporting the mast
3.17	0.6	3.13	Mode 1 of the deck
3.25	0.5	3.15	Mode 2 of the deck
3.40	0.7		Second mode of strip
3.96	0.8	3.98	Mode 3 of the deck
4.05	0.3	4.09	Mode 4 of the deck

Figure 6 also shows the peaks corresponding to the first natural frequencies of the cables, between 2.2Hz and 2.8Hz. The peaks in the higher frequencies correspond to the natural frequencies of the deck and, eventually, to the second natural frequencies of the strips and cables. The peaks at 3.17

and 3.25Hz as well as the peaks at 3.96 and 4.05 Hz correspond to approximately symmetrical mode shapes (see figure 7) and reflect the near-symmetrical shape of the deck.

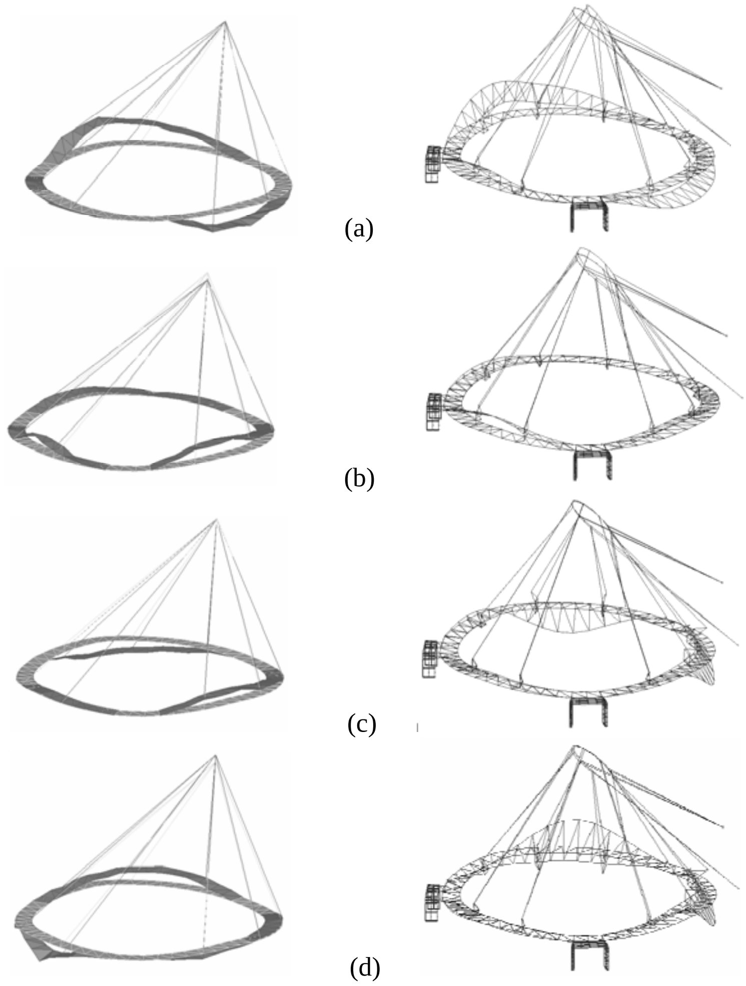

Figure 7 – Experimental vibration mode shapes of the deck

3.3 Dynamic response during pedestrian crossings

The vertical acceleration at points 1 to 8 (see figure 6) was recorded when groups of 65 pedestrians (about 46kN) crossed the bridge in synchronized walking. The pace rate was chosen to be 1.8Hz, 3.0Hz and 3.5Hz. Since the bridge is circular, the pedestrians did not leave the bridge during the test.

The maximum values of the acceleration and displacement obtained from the records after band-pass filtering between 0.5Hz and 25 Hz are summarized in table 4. The time histories had durations varying from 8 minutes, for the lower pace rate, and 1 minute, for the higher one.

The euro norm EN1990 gives the indicative maximum acceleration value of $0.7m/s^2$ for vertical movements of the deck during normal use. Considering that the first loading case in table 4 fulfils this requirement, the measured maximum values of acceleration are border line. However, if higher pace rates are considered, for instance 3.0Hz, corresponding to fast walking or normal running or 3.4Hz corresponding to rapid running, it can be concluded that the structure is prone to suffer much higher accelerations (see table 4).

Table 4 – Maximum accelerations and displacements obtained from the time histories after band-pass filtering between 0,5Hz and 25Hz.

	Sensor	**1**	**2**	**3**	**4**	**6**	**7**	**8**
Walking 1,8Hz	Acel. (m/s^2)	**0.87**	1.18	0.73	0.81	0.19	0.46	0.77
Duration: 8 minutes	Desl (mm)	1.2	1.3	2.0	1.7	0.5	1.1	1.3
Running 3,0Hz	Acel. (m/s^2)	3.02	3.10	3.22	**3.25**	1.12	3.05	3.10
Duration: 3 minutes	Desl (mm)	4.4	4.8	7.2	6.3	2.7	8.3	4.8
Running 3,4Hz	Acel. (m/s^2)	3.25	3.24	**3.65**	3.18	1.69	2.83	3.24
Duration: 1 minute	Desl (mm)	--	7.0	9.1	8.0	6.6	7.4	7.0

Although not measured, the vibrations in the stay-cables also increase significantly for those pace rates and fatigue problems can arise in the connections of the cables and of the steel strips to the mast and to the deck. This is perceptible if one looks at the natural frequencies in figure 6, where there are several peaks around 1.8Hz and 2.2Hz, which match the pace rates that are expected to occur during the service life of the structure. Furthermore, it is not to exclude that a situation of parametric excitation of the steel bands may occur for pace rates of about 3.4Hz.

However, during the tests it was not observed any synchronization between pedestrians and bridge.

4 Discussion and conclusions

Vibration measurements and modal identification of footbridges as part of commissioning tests are a very important tool to define and prepare necessary surveillance and eventual maintenance and repair works during its service life.

The structure analysed in this study presents a singular form, having a deck with circular configuration in plant, and is supported by stay cables and strips. The complexity of the dynamic response of such a bridge to pedestrian dynamic loadings is very difficult to foresee during design, mainly due to the interaction between the stay-cables and the deck itself.

The measurements carried out on this bridge were important in several ways. Firstly, they allowed the introduction of the right forces in the cables, so that the structural response could be the same as foreseen during design. Secondly, the modal identification of the bridge after conclusion of these works allowed a better interpretation of the dynamic response to the pedestrian loads and allowed to predict whether problems of excessive vibrations can occur or not. Finally, indicative maximum accelerations could be obtained for loading situations which the authors think can resemble very well common day-to-day situations during the service life.

Although the results concerning probable maximum accelerations of the deck for normal walking pedestrians are border line and for rapid walking and running are somewhat excessive, they should not be interpreted as being impeditive of a normal use of the bridge. However, the bridge owner must be aware that in some situations there can be an excessive vibration, which may frighten the users. Furthermore, attention must be paid to fatigue problems that can occur near the joints between the cables and the mast and deck.

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