IDENTIFICATION FROM THE NATURAL RESPONSE OF VASCO DA GAMA BRIDGE

Álvaro Cunha[1], Elsa Caetano[1], Rune Brincker[2], Palle Andersen[3]

[1]*Faculty of Engineering of the University of Porto, R.Dr. Roberto Frias, 4200-465 Porto, Portugal*
[2]*Dept. of Building Tech. and Structural Engineering, Aalborg University, Sohngaardsholmsvej 57, 9000, Denmark*
[3]*Structural Vibration Solutions, Novi Science Park, Niels Jernes Vej 10, 9220 Aalborg East, Denmark*
E-mail: acunha@fe.up.pt; ecaetano@fe.up.pt; i6rb@civil.auc.dk; pa@svibs.com

ABSTRACT

This paper describes the reanalysis of the ambient vibration data of Vasco da Gama cable-stayed bridge with the purpose of testing the efficiency and accuracy of two recent and promising identification methods in a large application: the Frequency Domain Decomposition (FDD) and the Stochastic Subspace Identification (SSI) methods. The modal estimates obtained using these alternative approaches are compared, taking also into account the estimates previously obtained with the conventional Peak Picking technique from the free vibration test of the bridge, performed at the end of construction.

1. INTRODUCTION

The Vasco da Gama Bridge is an outstanding structure located close to the area of EXPO'98 in Lisbon. At the end of construction and before the opening of the bridge to normal traffic, static and dynamic tests were performed to verify the corresponding safety conditions. The dynamic tests took place in March 1998 and consisted of an ambient vibration and a free vibration test, which were performed to accurately identify the most relevant natural frequencies, mode shapes and modal damping factors and correlate those identified parameters with the corresponding values obtained from the numerical modelling developed at the design stage. These tests, developed on the basis of an efficient wireless technique led to the creation of a high quality database characterising the initial dynamic behaviour of the structure, which was then processed using the conventional Peak Picking technique for the extraction of modal parameter estimates [1].

The recent development of new and promising output-only modal identification techniques for ambient vibration tests of large civil engineering structures seems however to open new perspectives in terms of the application of more automatic and accurate procedures for the estimation of modal parameters.

In this context, the present paper is focused on the reanalysis of the ambient vibration data of Vasco da Gama cable-stayed bridge with the purpose of testing the efficiency and accuracy of two recent and promising identification methods in a large application: the Frequency Domain Decomposition (FDD) [2] and the Stochastic Subspace Identification (SSI) [3] methods. The modal estimates obtained using these alternative approaches are compared, taking also into account the estimates previously obtained with the conventional Peak Picking technique from the free vibration test of the bridge.

2. THE VASCO DA GAMA BRIDGE

The Vasco da Gama Bridge is the second Tagus river crossing in Lisbon, with the total length of 17300m, involving three interchanges, a 5km long section on land and a continuous 12300m long bridge. This bridge includes a cable-stayed component over the main navigational channel with a main span of 420m and three lateral spans on each side (62m+70.6m+72m), resulting in a total length of 829.2m (Figure 1). The bridge deck is 31m wide and is formed by two lateral prestressed concrete girders, 2.6m high, connected by a cast in situ slab 0.25m thick and by transversal steel I-girders every 4.42m. The bridge is continuous along the total length and is fully suspended at 52.5m above the river by two vertical planes of 48 stays connected to each tower. The two H-shaped towers are 147m high above a massive zone at their base used as protection against ship collision. With regard to the stay cables, that consist of bundles of parallel self-protected strands covered by an HDPE sheath, specific protection against vibration was adopted, namely by inclusion of a double helical rib in the cable cover for prevention of rain wind vibration, and by use of innovative damper devices placed inside the steel guide pipe of the cables at the deck anchorages. Given the actively seismic location of the bridge site, specific measures were taken in the design of the bridge, namely the adoption of a full suspension deck from flexible towers in order to minimize the seismic forces. Additionally, a set of hysteretic steel dampers connecting the pylons and the deck were introduced, in order to limit the displacements. Under service loads, the transverse dampers work within the elastic range, acting as elastic supports, while the longitudinal dampers allow low speed displacements. In case of earthquake, use is made of the steel hysteresis to dissipate energy.

Fig. 1 – Cable-stayed component of Vasco da Gama Bridge

3 AMBIENT VIBRATION TEST

3.1 Description

The ambient vibration test was developed on the basis of 6 triaxial 16 bit strong motion recorders. Two recorders served as references, permanently located at section 10, 1/3rd span North on both sides of the bridge (Figure 2). Other two recorders were placed at section 15, serving also as references to confirm results. The other two recorders scanned the bridge deck and the towers using a total of 29 measurement sections. The expected interesting frequency range is very low (0-1Hz). Therefore the measurement time for each setup was chosen to be 16min, in order to capture enough periods of the low-frequency modes. The sampling frequency was 50Hz. The recorders were operating independently, but were programmed and synchronised by a portable PC. The excitation source was wind, of which the speed varied between 1m/s and 22m/s during the complete ambient vibration test campaign. This resulted in large differences of bridge acceleration magnitudes and, inevitably, in quality differences of the acquired data.

To verify the ambient vibration results, also a limited free vibration test was performed. The free vibration test allowed to accurately identify the modal damping ratios from the measured impulse responses. The experimental identification of damping ratios is very important because there is no reliable analytical approach available for their evaluation and because they have a large influence on the bridge response to earthquake and wind excitation. An impulsive excitation was obtained by suspending a mass of 60t from a point on the bridge deck, close to location 10 (upstream) (Figure 2), and suddenly releasing it. The resulting free vibrations were then recorded during 16min at measurement sections 10, 13 and 16 (Figure 2). This test was performed under low wind speeds (less than 2.5m/s were measured), so that there was not much undesired ambient excitation and the identified damping ratios represented the real structural damping ratios, with no added aerodynamic component.

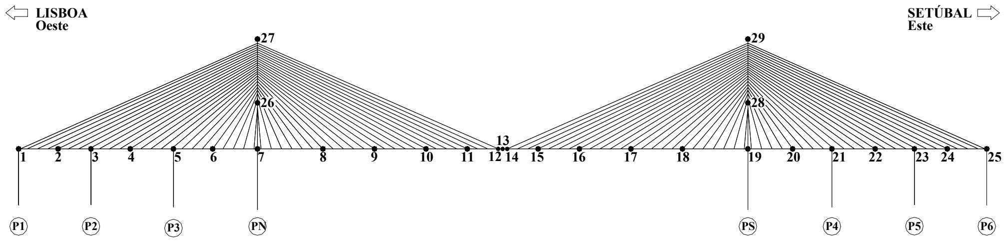


Fig. 2 - Measurement locations on the Vasco da Gama cable-stayed bridge

3.2 Data properties from preliminary signal processing

The data, originally sampled at 50 Hz, was decimated 20 times and high-pass filtered to remove any offset and drift. The decimation (anti-aliasing) filter was an 8th order Chebyshev Type 1 low-pass filter cutting off at 1 Hz and the high-pass filter was a 2nd order Butterworth filter cutting off at 0.01 Hz. After decimation, the number of samples in each record was of 2402 with a sampling interval of 400 ms, corresponding to a sampling frequency of 2.5 Hz and a Nyquist frequency of 1.25 Hz. Subsequently, data was processed in order to estimate spectral densities with 256 frequency lines and a frequency line spacing of 4.883 mHz. This was achieved using an overlapping of 66.67% and applying a Hanning window.

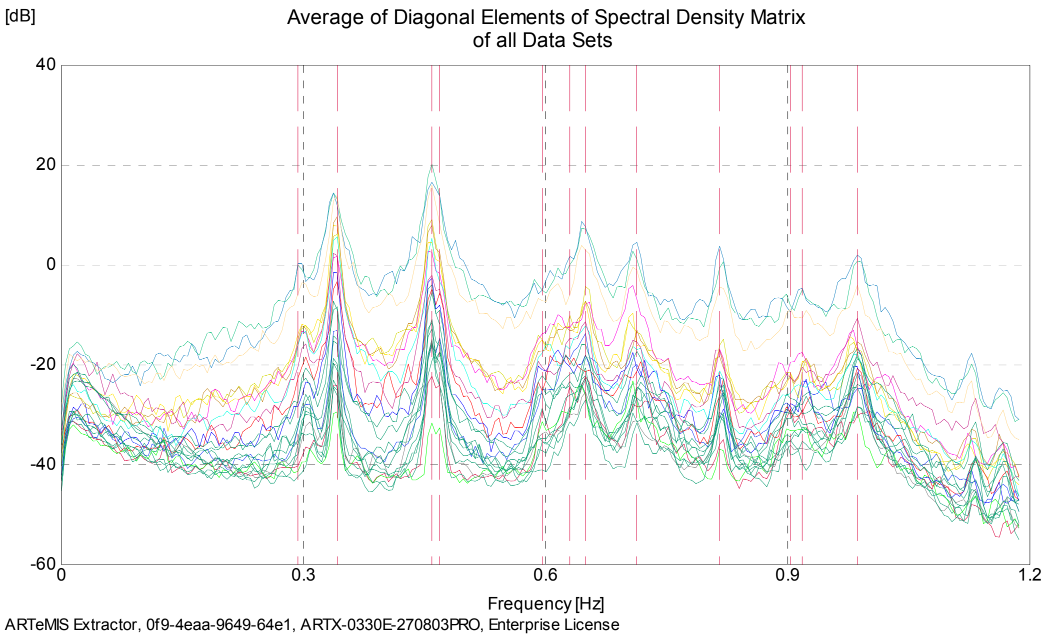


Fig. 3 – Sum of the diagonal elements of the spectral matrix for the four reference sensors for 24 data sets (dashed lines indicate 12 identified modes)

The analysis of the several data sets acquired in the ambient vibration test could show that the ambient conditions varied significantly during the period of two days and a half used for its performance. During this period, the wind speed measured at midspan oscillated between 1 and 22 m/s. Accordingly, the maximum r.m.s. acceleration values at the reference section 10, in the several data sets, were 0.13mg (longitudinal, X), 0.35mg (transversal, Y) and 1.69 mg (vertical, Z), whereas the corresponding minimum r.m.s. values were 0.03mg, 0.03mg and 0.06mg, respectively. This aspect is also evidenced by Figure 3, which shows the sum of the diagonal elements of the spectral matrix for the four reference sensors for 24 data sets. This figure shows that there is a difference in excitation level between the highest and the lowest excited data sets of about 40dB, corresponding to a factor of 100. Inspection of the spectral densities of the measured response at the different data sets shows a large difference between the data sets. In some data sets, 12 modes are reasonably clearly represented, whereas in other data sets the contribution of some of the modes has nearly vanished or the spectral peaks have shifted.

4 MODAL PARAMETER IDENTIFICATION

The identification of modal parameters of the bridge was developed, in this work, using the Frequency Domain Decomposition (FDD) and the Stochastic Subspace Identification (SSI) methods, implemented in the software package ARTeMIS [4].

4.1 Modal identification by Frequency Domain Decomposition (FDD)

By performing a Singular Value Decomposition of the spectral densities matrix associated to each measurement setup, it was possible to evaluate the corresponding non-zero singular values. Figure 4 shows, for instance, a plot of non-zero singular values related with the setup involving measurements at sections 4 and 10. Inspection of these plots shows that 12 modes are reasonably well represented in all the 24 analysed data sets, though some more modes are probably present, namely in the vicinity of 0.60 and 0.75 Hz. Table 1 summarizes the identified natural frequencies, as well as the standard deviations of the corresponding estimates. It is worth noting that no damping was estimated. In fact, the frequency resolution adopted was relatively low, in order to guarantee a significant number of averages, essential for good performance of the FDD technique, and so that would lead certainly to an unacceptable amount of leakage bias on the damping estimates when using the enhanced FDD for damping analysis.

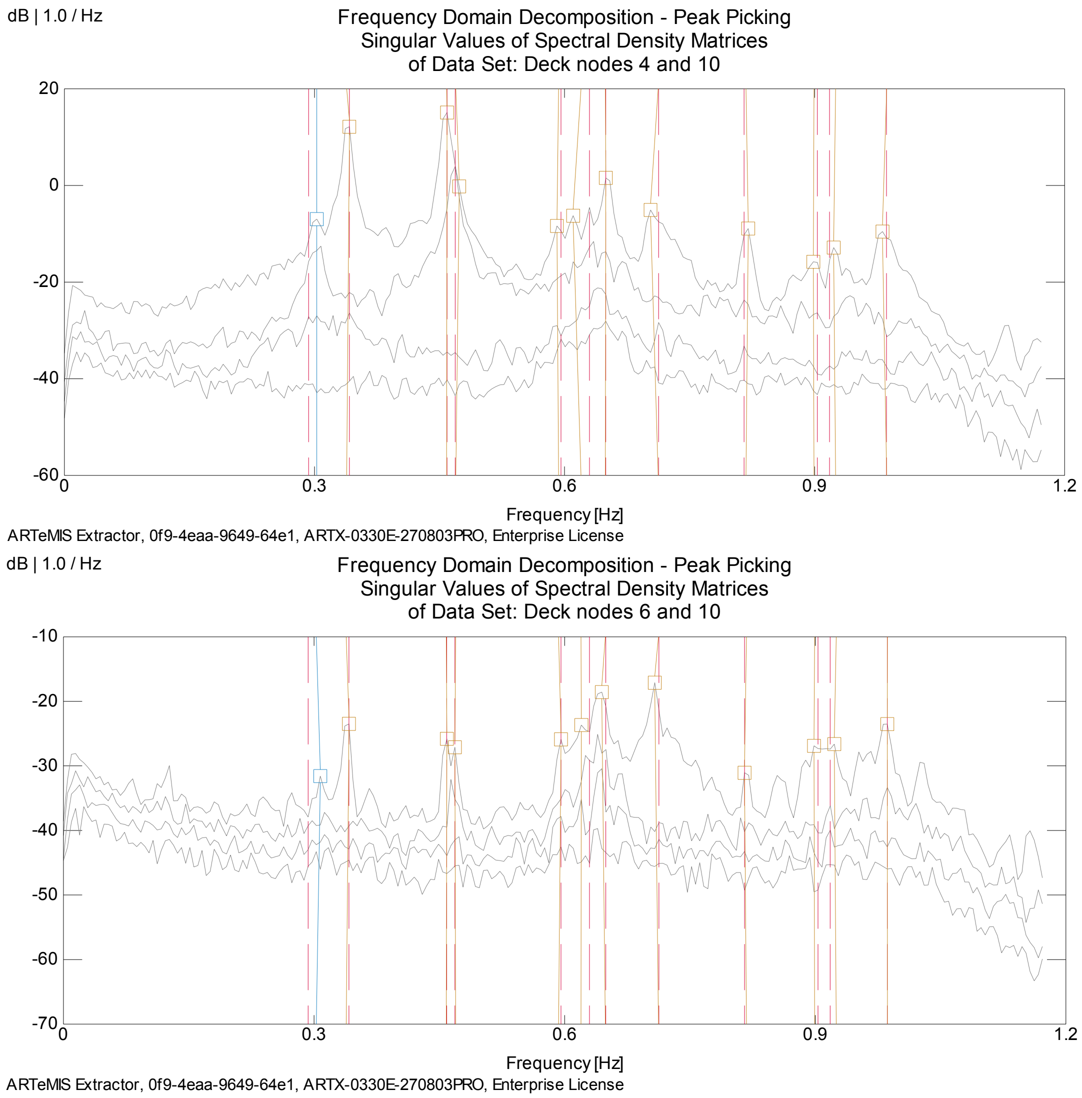


Fig. 4 – FDD plot for data sets 4 and 6 (sections 4 and 10, and 6 and 10)

Table 1: Identified natural frequencies and modal damping ratios

Mode	FDD estimates		SSI estimates			
	Frequency (Hz)	Rel. Std. Dev. (%)	Frequency (Hz)	Rel. Std. Dev. (Hz)	Damping Ratio (%)	Rel. Std. Dev. (%)
1	0.3027	1.65	0.3025	1.56	1.246	44
2	0.3385	0.69	0.3391	0.27	0.3328	73
3	0.4584	0.36	0.4578	0.14	0.2616	64
4	0.4696	0.4	0.4685	0.3	0.2884	58
5	0.5929	0.68	0.5956	0.78	0.8016	81
6	0.6197	1.29	0.6274	0.98	0.8354	67
7	0.6488	0.46	0.6499	0.32	0.6034	58
8	0.7123	0.74	0.7142	0.76	0.8948	46
9	0.8177	0.3	0.818	0.26	4.523	450
10	0.8993	0.55	0.8995	0.75	0.7447	57
11	0.9251	0.81	0.9188	0.54	0.7198	53
12	0.9865	0.45	0.988	0.47	1.111	233

4.2 Modal identification by Stochastic Subspace Identification (SSI)

In most of the data sets, proper models were identified by the SSI method with a model order of 60-100, i.e. models containing 30-50 modes. This means that the correct estimation of the 12 modes previously identified by the FDD technique involved the consideration of at least 5-8 times more noise modes. The search for the best models was based on the construction of stabilization diagrams. Figures 5 and 6 show typical stabilization plots associated to the data sets involving measurements at sections 4 and 10, and 6 and 10. Inspection of these plots shows that all the 12 modes are reasonably well represented in all the 24 data sets analyzed, though some extra poles (stabilizing like physical poles) have been found around 0.60 and 0.90 Hz. Table 1 summarizes also the identified natural frequencies and modal damping factors, as well as the standard deviations of the corresponding estimates. Also for the SSI the relative uncertainties on the natural frequencies are of the order of 1 %. It is believed that this uncertainty is mainly influenced by the fact that frequencies have probably shifted from data set to data set due to changes in temperature and loading conditions. However, some uncertainty related with choosing the right pole among a large number of noise poles may have also contributed to that uncertainty.

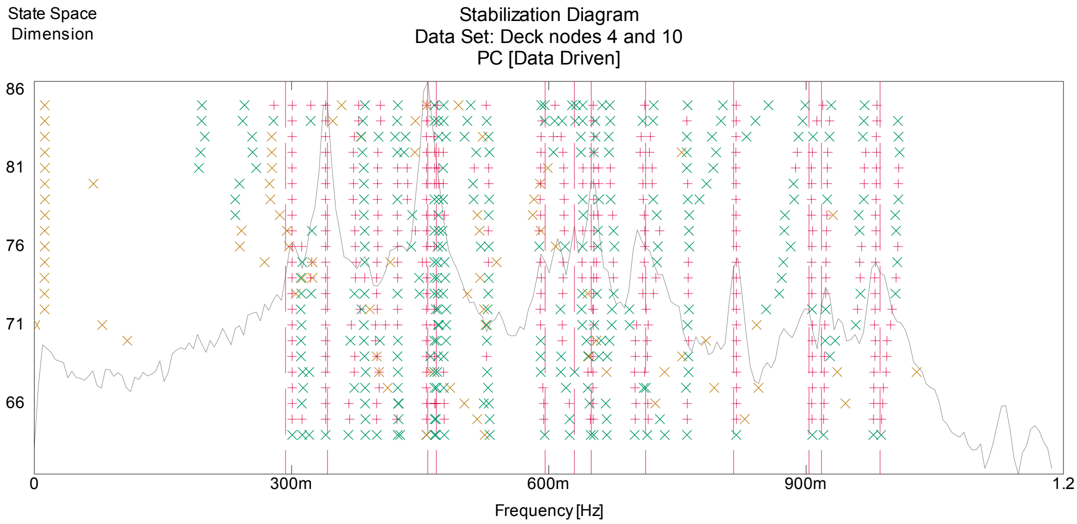


Fig. 5 – Stabilization diagram for data set 4 (measurement sections 4 and 10)

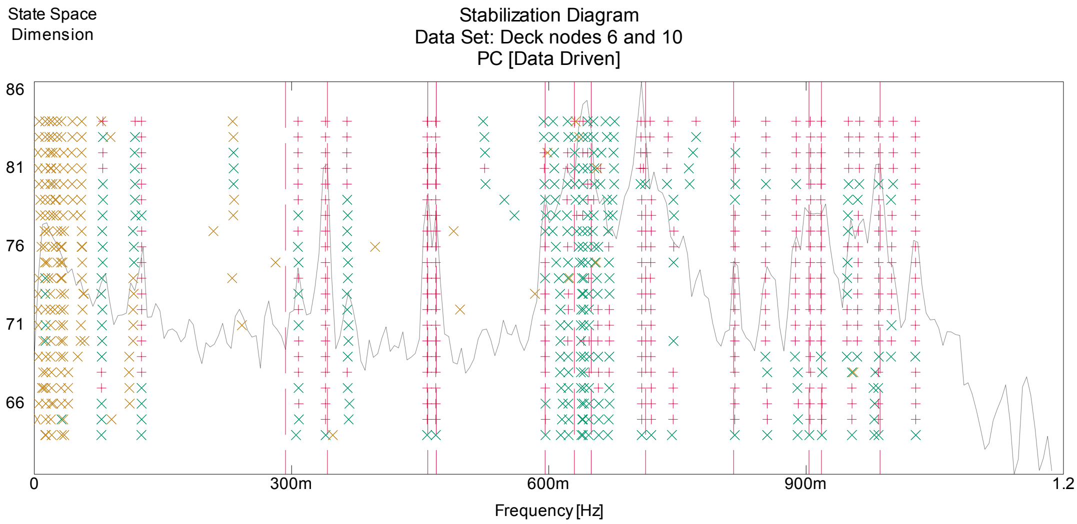


Fig. 6 – Stabilization diagram for data set 6 (measurement sections 6 and 10)

Concerning the damping estimates, it can be concluded, that the modal damping ratios are typically of the order 0.3 – 1 %. However, since the data is rather limited, and since the SSI is only asymptotically unbiased, it must be expected that these estimates are biased, and thus lower damping values should be expected if longer time series were obtained. Also it should be noted that the damping estimate for mode 9 seems unrealistically high.

4.3 Comparison of FDD and SSI modal estimates

Table 2 resumes the values of natural frequencies and modal damping ratios identified on the basis of the FDD and SSI methods, as well as of the corresponding values previously measured by Peak Picking (PP) in the free vibration test (FVT) [1]. As shown in this table, the application of FDD and SSI methods led to very close estimates of natural frequencies of the bridge, which are consistent with the PP(FVT) estimates. Beyond that, the modal damping estimates provided by SSI are also in rather good agreement with the measured values at the free vibration test, despite their higher level of uncertainty. With regard to the FDD and SSI estimates of mode shapes, they were compared using the MAC matrix shown in Figure 7. This figure shows that modes 1,2,3,4,7,8,9,11 and 12 were estimated with a MAC value higher than 0.9, whereas modes 5,6 and 10 (specially mode 6) were estimated with a lower MAC value.

Table 2: Identified natural frequencies and modal damping ratios

Mode	Nat. freq.(Hz)			Damping Ratios (%)	
	PP (FVT)	FDD	SSI	PP (FVT)	SSI
1	0.295	0.303	0.303	1.23	1.25
2	0.338	0.339	0.339	0.21	0.33
3	0.456	0.458	0.458	0.23	0.26
4	0.467	0.470	0.469	0.24	0.29
5	0.591	0.593	0.596	0.34	0.80
6		0.620	0.627		0.84
7	0.647	0.649	0.650	0.37	0.60
8	0.707	0.712	0.714	0.78	0.89
9	0.814	0.818	0.818	0.48	4.52
10		0.899	0.899		0.74
11		0.925	0.919		0.72
12	0.982	0.987	0.988	0.74	1.11

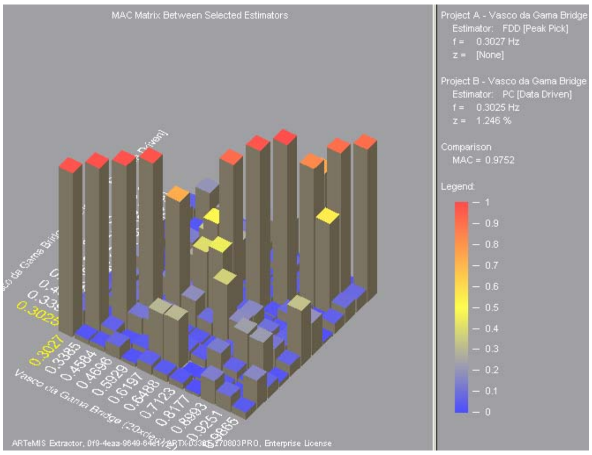
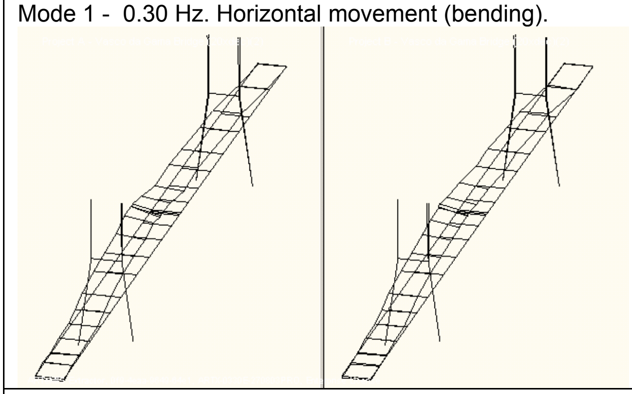
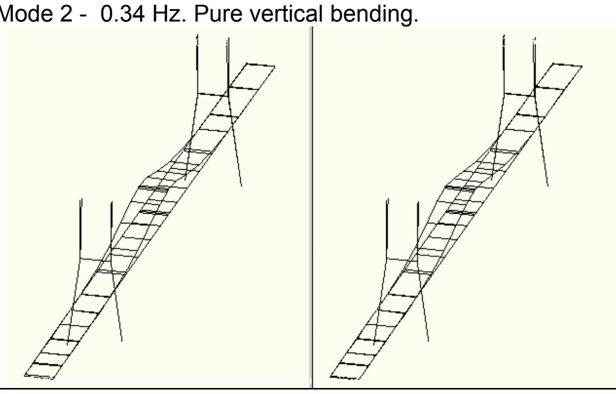
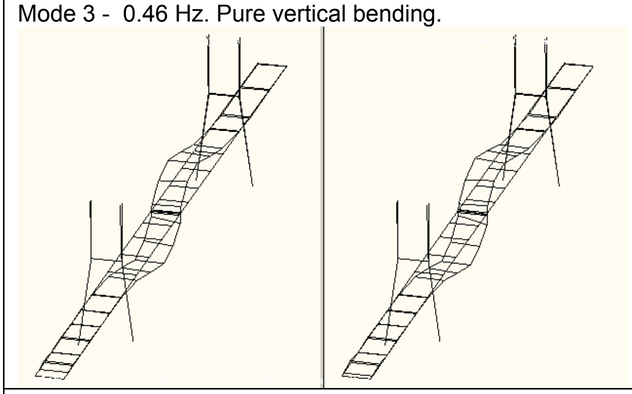
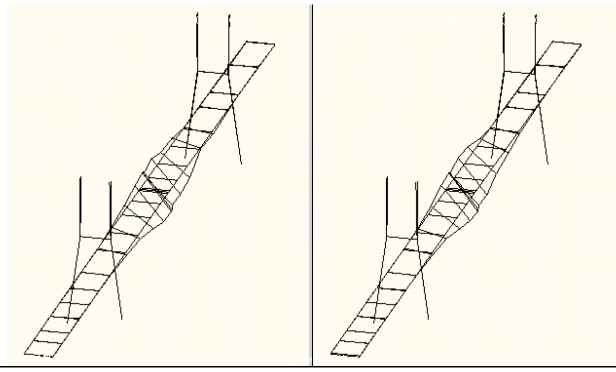
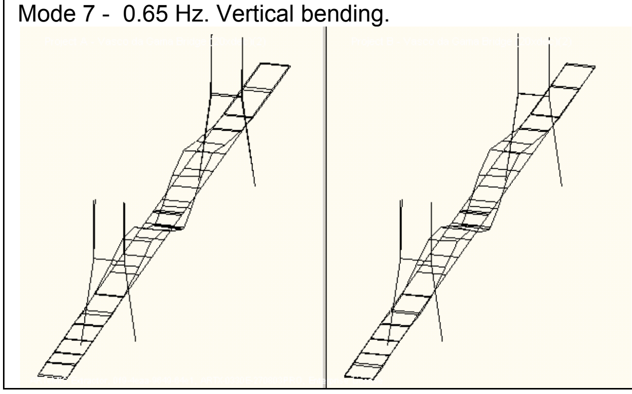
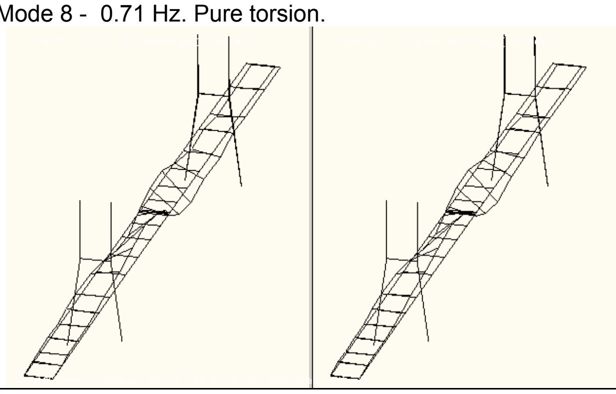


Fig. 7 – MAC matrix plot for mode shapes estimated by FDD and SSI methods

Mode 1 - 0.30 Hz. Horizontal movement (bending). 	Mode 2 - 0.34 Hz. Pure vertical bending. 
Mode 3 - 0.46 Hz. Pure vertical bending. 	Mode 4 - 0.47 Hz. Pure torsion. 
Mode 7 - 0.65 Hz. Vertical bending. 	Mode 8 - 0.71 Hz. Pure torsion. 

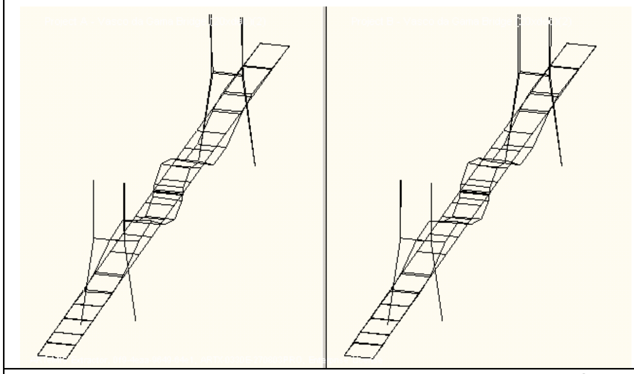
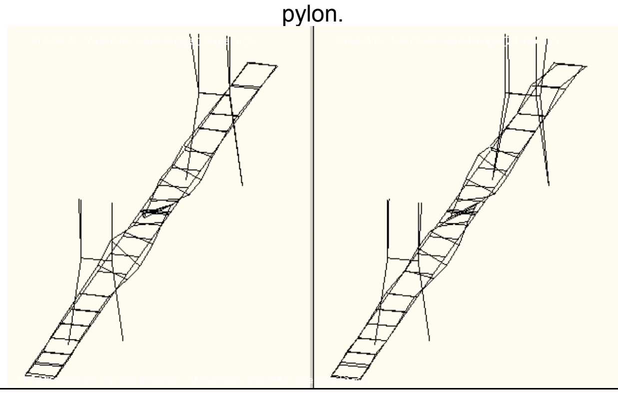
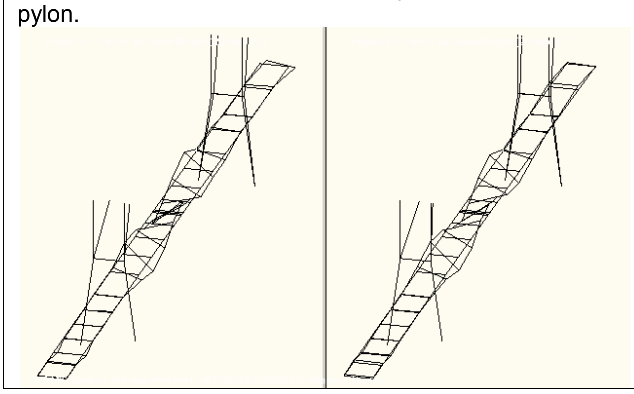
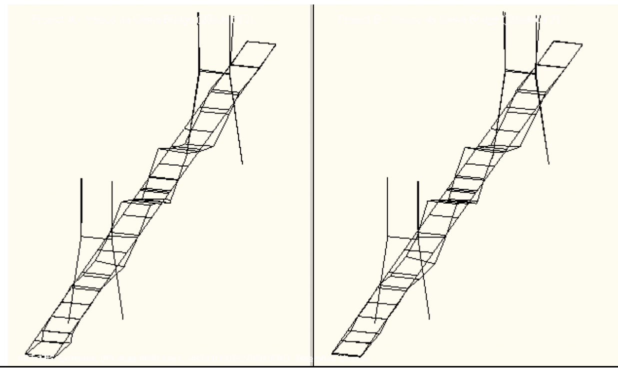
Mode 9 - 0.82 Hz. Pure vertical bending. 	Mode 10 - 0.90 Hz. Pure torsion, large movements in back pylon. 
Mode 11 - 0.92 Hz. Pure torsion, large movements in front pylon. 	Mode 12 - 0.99 Hz. Pure vertical bending. 

Fig. 8 – Most relevant mode shapes identified by FDD (left) and SSI (right) methods

5 CONCLUSIONS

The present reanalysis of the ambient vibration data of Vasco da Gama cable-stayed bridge could show that both the Frequency Domain Decomposition (FDD) and the Stochastic Subspace Identification methods are powerful methods that allow an objective identification procedure, providing sufficiently accurate estimates of natural frequencies and mode shapes of large bridges. With regard to the identification of modal damping ratios, which can play a very important role in terms of aerodynamic stability of this type of structures, the SSI method seems to enable rather satisfactory estimates, in comparison with accurately measured values in a free vibration test previously performed at the end of construction, despite some limitations associated to the relatively reduced time of acquisition in each measurement setup.

REFERENCES

1. Cunha Á., Caetano E. and Delgado, R., "Dynamic Tests on a Large Cable-Stayed Bridge. An Efficient Approach", *Journal of Bridge Engineering*, ASCE, Vol. 6, No.1, pp.54-62, 2001.
2. Brincker R., Zhang L. and Andersen P., "Modal identification from ambient responses using frequency domain decomposition", In *Procceedings of IMAC-XVIII, International Modal Analysis Conference*, pp.625-630, San Antonio, Texas, USA, 2000.
3. Van Overschee, P., De Moor, B., "*Subspace Identification for Linear Systems: Theory-Implementation-Applications*", Kluwer Academic Publishers, Dordrecht, The Netherlands, 1996.
4. http://www.svibs.com