Modal Identification of a Pedestrian Bridge by Output-Only Analysis

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ABSTRACT

Modal parameters (natural frequencies, mode shapes and damping ratios) describe the dynamic properties of mechanical systems. Classical modal analysis, based on Frequency Response Function, require measurement of both input force and response. Normally, it is very difficult to measure the excitation on large structures (bridges, tall buildings, offshore platforms, etc.). However, reasonable estimates of modal parameters can be extracted from ambient vibration or output-only response (wind, traffic, humans, etc.).

The dynamic behaviour of a curved pedestrian bridge in the Cartuja Campus of the Universidad de Sevilla (Spain) has been investigated by full-scale testing and numerical models. Nine vibration modes have been identified in the frequency range of 0-30 Hz, by the following algorithms: Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI).

Modal parameters estimated from ambient response are compared with those obtained from a three-dimensional finite element model. Both sets of results show very good agreement.

1. INTRODUCTION

Several techniques to obtain dynamic parameters of structures from experimental measurements have been developed in the last three decades. Accurate estimations of modal parameters can be obtained from the measured response of structures to their service loads (wind, traffic, etc). Operational Modal Analysis (OMA) and some auxiliary techniques have been used to obtain dynamic parameters of different structures [1,2,3,4]. Experimental measures of dynamic parameters can be used to asses the actual strength of structures that have suffered an earthquake, attack or accident, or simply, historical structures that were constructed under completely different conditions and have been in service for hundreds of years. Also to determine parameters needed for the FE analysis of existing structures.

In the present paper, the essays carried out over a curved concrete bridge at the Cartuja Campus of the Universidad de Sevilla are first described. Ambient vibration was measured at different points of the bridge deck. Then, modal parameters are obtained by using OMA and two different identification techniques; i.e., Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI). The obtained results are compared with those computed using a Finite Element model. The agreement between both sets of results is shown to be very good.

Figure 1. View of the structure.

2. DESCRIPTION OF THE STRUCTURE

The curved bridge over the North Canal of the Cartuja Campus of the Universidad de Sevilla, was built in 1990 for pedestrian use, to be eventually transformed for traffic of vehicles within the “Isla de La Cartuja” an area specially developed for the Universal Exhibition EXPO-92 (Figure 1).

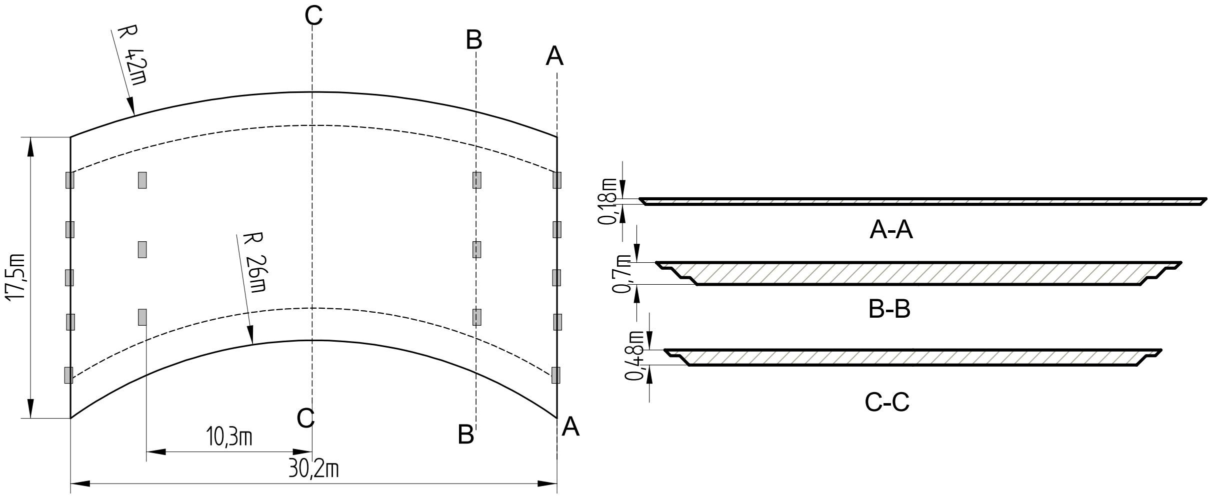


Figure 2. Plan and deck cross-section of the structure (dimensions in metres).

The three span deck is 16.6 m wide and its length is 32.6 m. The internal radius of the circular curved deck is 26 m and the external one is 42 m (Figure 2).

The structure consists of a prestressed concrete deck with variable cross-section and six reinforced concrete columns. The deck is simple supported on the abutments at five points spaced 5.2 m.

3. FINITE ELEMENT ANALYSIS

A 3D finite element model (Figure 3) was developed using as-built drawings of the bridge and in-situ measurements. The model includes 15888 degrees of freedom and 2942 elements. The deck was modelled using 2612 six-node shell elements with 6 degrees of freedom per node. The non-uniform deck cross-section was considered by using elements with different cross section properties and an off-set between elements with different width. The columns were modelled using 36 3D beam elements. The design data suggested a Young´s modulus of 40 GPa for the prestressed concrete of the deck and a value of 35 GPa for the columns. A Poisson`s ratio of 0.15 for the concrete of both deck and columns was considered.

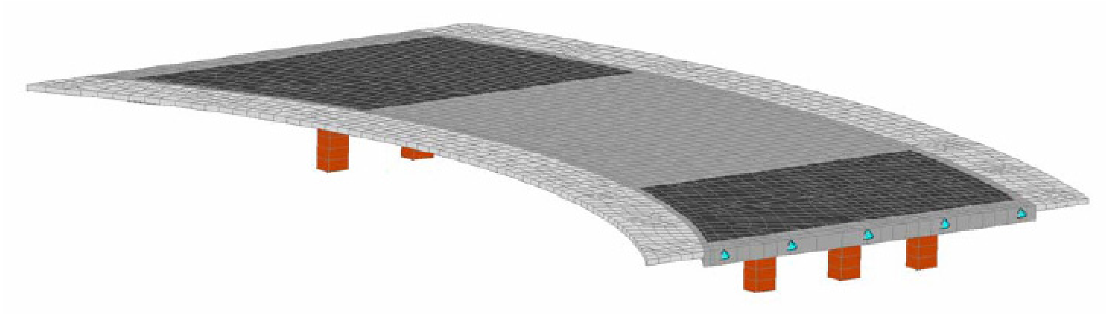


Figure 3. 3D finite element model.

It was clear from the pre-test finite element analysis that a great portion of the structure dynamic response should be associated with vertical motion of the deck; and a group of modes associated with the local behaviour of the external edges of the bridge. It can be seen from Figure 4 that mode 1,2,3 and 9 correspond to a global motion of the structure whereas modes 4,5,6,7 and 8 are associated with local deformation of the internal and external pedestrian decks of the bridge.

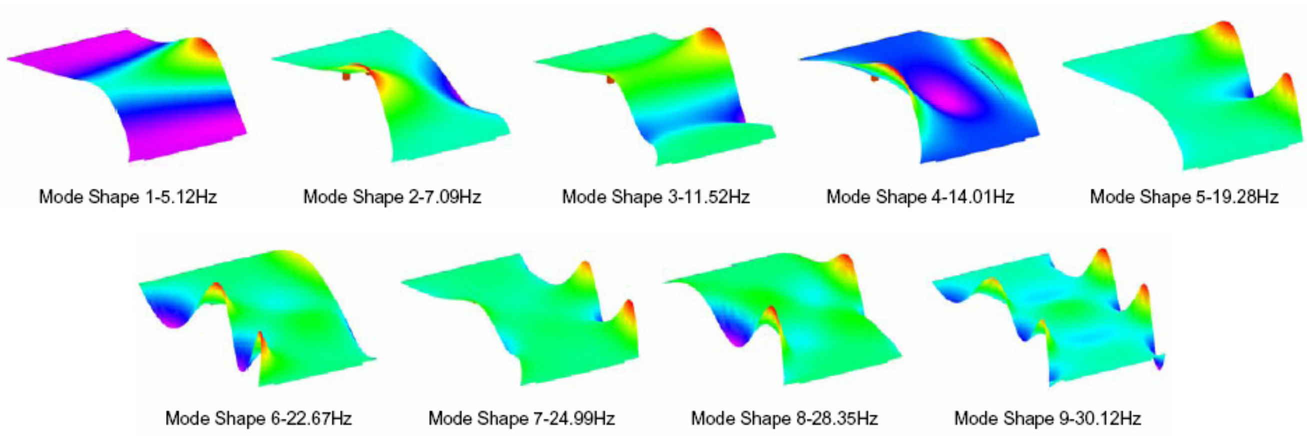

Mode Shape 1-5.12Hz
Mode Shape 2-7.09Hz
Mode Shape 3-11.52Hz
Mode Shape 4-14.01Hz
Mode Shape 5-19.28Hz
Mode Shape 6-22.67Hz
Mode Shape 7-24.99Hz
Mode Shape 8-28.35Hz
Mode Shape 9-30.12Hz

Figure 4. Results from finite element analysis.

The results from the dynamic analysis of this FE model were used to determine the location of the sensors.

4. FULL-SCALE TESTING

The response of the structure was measured at selected points using Endevco (Model 86) piezoelectric accelerometers. These accelerometers have a nominal sensitivity of 1000 mV/g and a low frequency limit of approximately 0.1 Hz. Since a maximum of nine accelerometers was available for the testing and two of these sensors were held stationary for reference measurements, five set-ups was required to cover the 35 measurement points. In output-only modal analysis where the input force remains unknown and may vary between the set-ups, the different measurements setups can only be linked if there are some sensors in common.

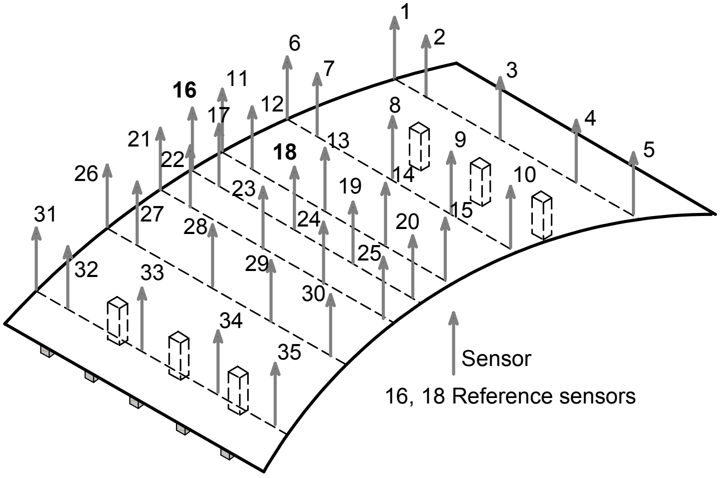


Figure 5. Measurement locations.

The test was carried out during May 2004. Data acquisition was performed using a Brüel&Kjaer portable spectrum analyser with twelve input channels. Ambient vibration (resulting from the wind, traffic and people) response was acquired in 500 seconds per channel per set-ups and the signals were sampled at approximately 82 Hz. The cut-off frequency of the anti-aliasing filter was 40 Hz. The length of time series was 40985 data per channel.

5. DATA PROCESSING AND ANALYSIS

Different procedures were used to extract the modal parameters from ambient vibration data based on the classical spectral techniques [5,6]; Enhanced Frequency Domain Decomposition algorithm (EFDD) [7]; and

Stochastic Subspace Identification algorithm (SSI) [8] were used for estimation of modal properties using output-only modal identification. The analysis was performed by using ARTeMIS software (developed by Structural Vibration Solutions).

The EFDD technique is based on decomposition the power spectral density matrix using the singular value decomposition (SVD). In this way, the response spectra can be separated into a set of single degree of freedom systems, each corresponding to an individual mode. Figure 6 shows SVD of the spectral density matrix.

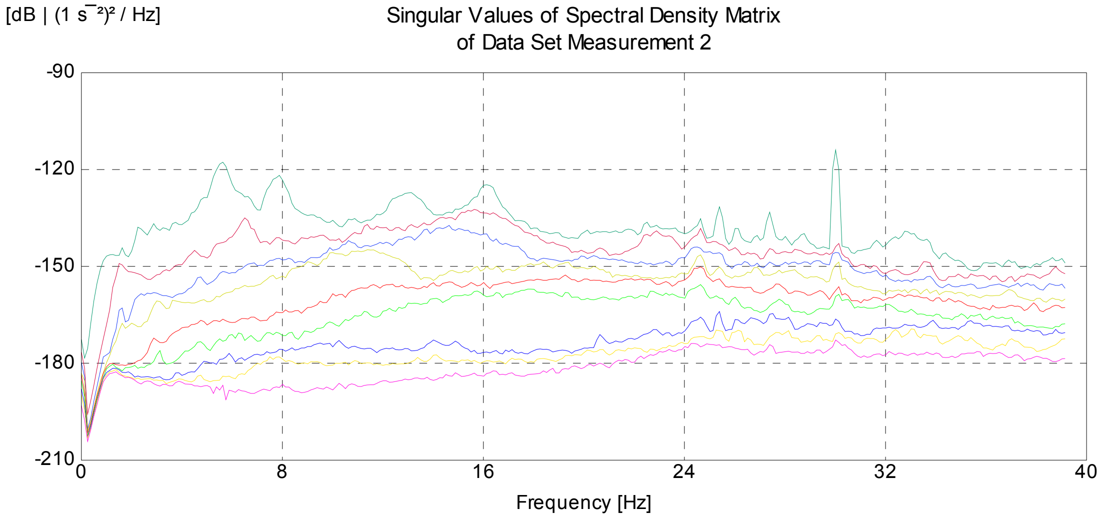


Figure 6. SVD of the spectral density matrix.

The stochastic subspace identification method identifies a stochastic state space model from output-only measurements. The state space model is a very general model that is also suitable for describe a linear vibrating structure. For each set-up a set of models with different model orders are identified and the stabilisation diagram is established. Figure 7 shows the stabilisation diagram for set-up two.

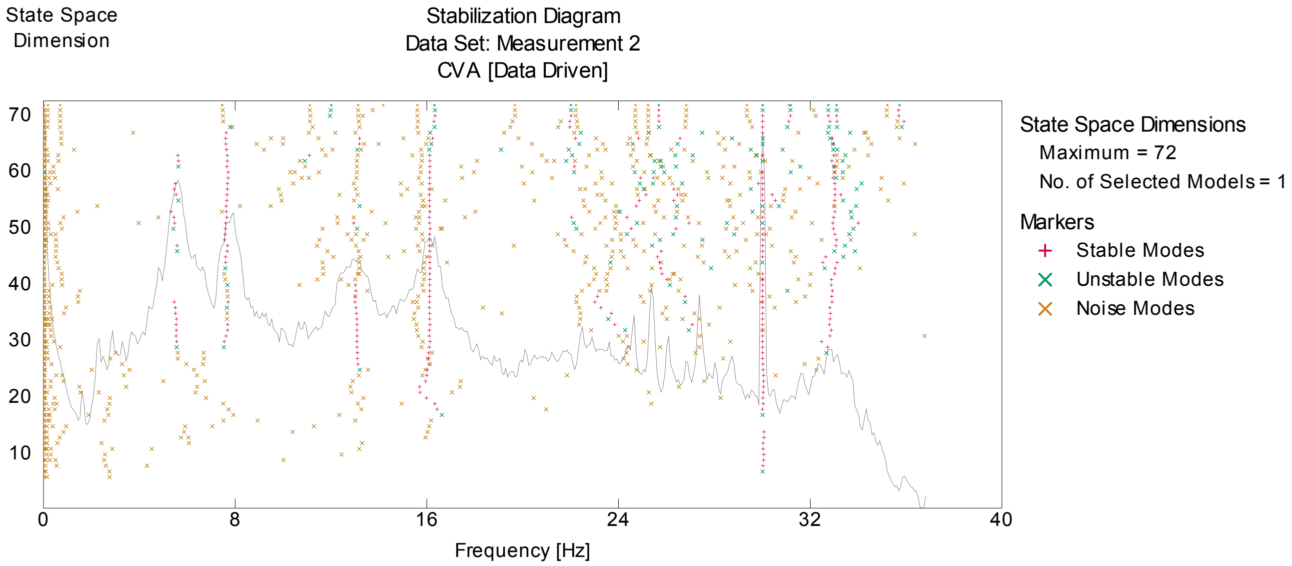


Figure 7. Stabilisation diagram for set-up two.

6. DYNAMIC BEHAVIOUR

Nine vibration modes were identified output-only measurements in the frequency range 0-30 Hz. The results of ambient vibration testing and FE analysis are presented in Table 1. The nine modes of vibration yielded by both techniques were very close one to each other.

$f_{EFDD}(Hz)$	$f_{SSI}(Hz)$	$f_{FEM}(Hz)$	$\xi_{EFDD}(\%)$	$\xi_{SSI}(\%)$
5.588	5.676	5.12	2.992	2.144
7.95	7.6	7.09	2.769	3.649
13.73	13.05	11.52	3.867	4.341
16.19	16.16	14.01	2.095	1.998
20.01	19.19	19.28	1.525	3.864
24.64	24.83	22.67	4.655	4.051
25.97	25.92	24.99	0.417	0.878
29.52	29.6	28.35	2.183	2.138
30.02	30.21	30.12	3.245	4.032

Table 1. Results.

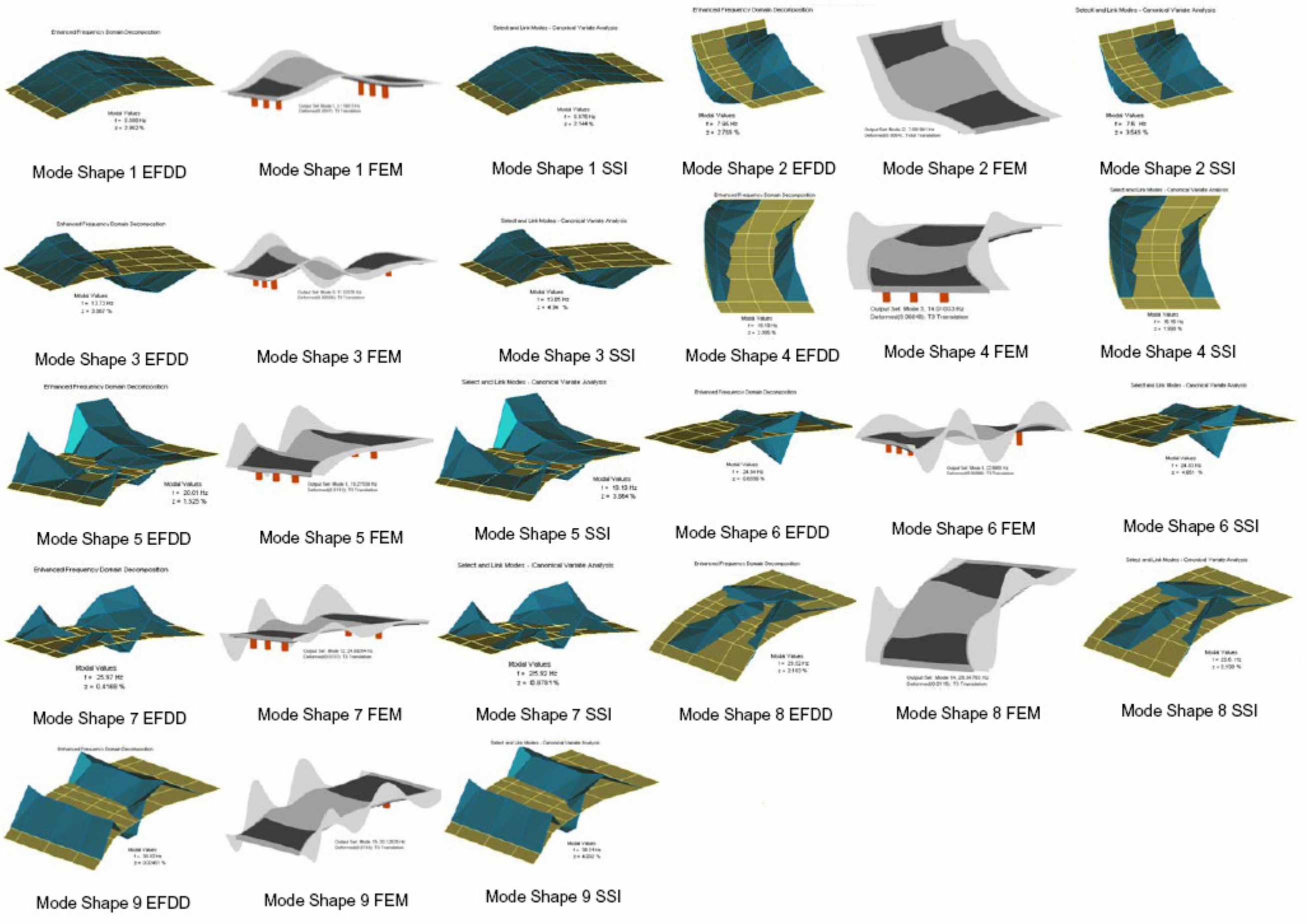
The modes of vibration measured on the structure can be grouped into two categories, those associated mainly with vertical motion of the deck (Modes 1,2,3,9) and those associated with the local behaviour of the edges of the bridge (Modes 4,5,6,7,8). These results showed very good agreement with those obtained from the finite element analysis. Damping ratios ($\xi < 5\%$) are expected in this type of structures.

In order to compare the estimated mode shapes, the Modal Assurance Criterion (MAC) was used. The experimental modes of vibration correlate very well with finite element analysis as can be seen in Figure 8.

7. CONCLUSIONS

One of the main purposes of this paper was to validate the use of some techniques based on low level environmental excitation to determine dynamic parameters of structures. FE results are compared with those obtained from experimental measurements. The agreement of natural frequencies and mode shapes obtained from both types of techniques is very good. Modal Assurance Criterion (MAC) has been used for comparison of obtained mode shapes. Both identification techniques (Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification) give good results with less computational effort required for the Enhanced Frequency Domain Decomposition.

Results obtained for the Alamillo Bridge in Seville will be presented in a forthcoming paper.



Mode Shape 1 EFDD
Mode Shape 1 FEM
Mode Shape 1 SSI
Mode Shape 2 EFDD
Mode Shape 2 FEM
Mode Shape 2 SSI
Mode Shape 3 EFDD
Mode Shape 3 FEM
Mode Shape 3 SSI
Mode Shape 4 EFDD
Mode Shape 4 FEM
Mode Shape 4 SSI
Mode Shape 5 EFDD
Mode Shape 5 FEM
Mode Shape 5 SSI
Mode Shape 6 EFDD
Mode Shape 6 FEM
Mode Shape 6 SSI
Mode Shape 7 EFDD
Mode Shape 7 FEM
Mode Shape 7 SSI
Mode Shape 8 EFDD
Mode Shape 8 FEM
Mode Shape 8 SSI
Mode Shape 9 EFDD
Mode Shape 9 FEM
Mode Shape 9 SSI

Figure 8. Mode shape from ambient vibration and from finite element analysis.

8. ACKNOWLEDGMENTS

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