Operational Modal Analysis of a Historic Tower in Bari

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ABSTRACT

In this paper, the latest identification techniques both in the time and in the frequency domains, are applied to the data obtained from the dynamic monitoring of the reinforced concrete tower of the Provincial Administration Building of Bari (Italy). The tower, dating back to the thirties of the 20th century and about 60 m tall, is not only a typical example of the fascist architectural style, but it is an important symbol of the city itself.

The extraction of the modal parameters from ambient vibration data has been carried out by using the ARTeMIS Extractor Pro 2010 software. Three different Operational Modal Analysis (OMA) methods have been utilized: EFDD, SSI and Crystal Clear-SSI. The first two couples of bending mode shapes are also estimated and shown.

1.INTRODUCTION

The present study has been performed in order to identify the modal parameters of an important historical building, the tower of the Provincial Administration Building in Bari, Italy, with the final purpose to predict the performance of the tower to different combinations of static and dynamic loads, such as earthquakes or other induced vibrations.

In the last years, structural identification has received great attention due to its possibility of giving a complete description of the dynamic behavior of the structures, especially for monitoring existing structures. In this field, in fact, an important role is played by the identification techniques applied to ambient vibrations, in case of historical buildings for which the use of artificial dynamical excitation may not be possible. In particular, ambient vibration testing has become the main experimental method available for assessing the dynamic behavior of full-scale structures [1] because no excitation equipment is needed, involving a minimum interference with the normal use of the structure. The procedure is especially suitable for flexible systems, such as civic towers [2], bell-towers [3-6], masonries [7] and minarets [8].

One main problem in the Operational Modal Analysis (OMA) is the maintenance of the data acquisition system [9]. Field measurements, in fact, are often performed in very harsh environmental conditions, requiring high accuracy both in the control of the test set-up and in the analysis of the measured data. Moreover, measurements are usually noisy for the necessity of using very long cable transducers. Other relevant and common problems in the field of OMA are [10]: the difficulty to detect different mode shapes for very closely spaced modes; the subjectivity in the system order estimate; the need of a more efficient algorithm able to omit the spurious modes created by noise or redundant degrees of freedom of the model.

Ambient vibration tests have been carried out on the tower of the Provincial Administration Building in Bari, in a particularly windy day (24th July 2009), with the aim of determining its dynamic response and developing a procedure for modeling the tower. The Operation Modal Analysis has been performed both in the frequency domain and in the time domain to extract the dominant frequencies and mode shapes. The application of well-known identification techniques - the Enhanced Frequency Domain Decomposition (EFDD) [11], the Stochastic Subspace Identification (SSI) [12] and the Cristal Clear-SSI (CC-SSI) methods [13], the last recently implemented in a commercial software, yields to very similar results (in both frequencies and mode shapes) for all the identified modes, providing consistent information for the updating of the finite element model of the tower..

2.DESCRIPTION OF THE BUILDING

The tower of the Provincial Administration Building in Bari, Italy (Fig.1), dating back to the thirties of the 20th century and about 60 m tall, is not only a typical example of the fascist architectural style, but it is an important symbol of the city itself.

Fig. 1. View of the Provincial Administration Building of Bari (a) and of the investigated tower (b)

Situated on the waterfront of the city, with the principal façade exposed to the North-West direction (that is the dominant wind direction), the tower has eleven floor, characterized by different heights, and a square plan with a side of about 9,0 m from the base to the 5th floor, a side of about 8,6 m from the 5th to the 9th floor, a side of about 7,6 m at the 10th floor, and a side of about 5,3 m at the 11th floor. It is made of massive concrete reinforced with a diffuse and superficial reinforcement and it stands on a foundation slab. The eleven levels of the tower consist of a basement, a mezzanine and nine floors. Up to the 5th floor, the tower is included in the main part of the building of the provincial administration, from which it emerges for six levels more (Figure 1), from 6th to 11th ones, with openings on the façades in the first floor up to the building of the provincial administration and in the upper two floors, the last of which (the bell chamber) has a smaller plan with respect to the others.

The tower was instrumented with thirteen SA-107LNC uniaxial servo-accelerometers placed at floors 5, 7, 9 and 10 and connected to a centralized data acquisition board by means of long transducer cables (Fig. 2). The accelerometers position along the height of the tower, referred to the xyz reference system is shown in Fig.3a while the quoted sections of the instrumented tower floors are showed in Fig.3b. The response obtained was registered by a HBM MGC Plus at a sample rate of 200 Hz. The signal conversion and the data acquisition were managed by a laptop in the framework of the CATMANv4 software package, which included an analogical filter with a cut-off frequency of 40 Hz.

Fig. 2. Accelerometers and acquisition board used for the tests.

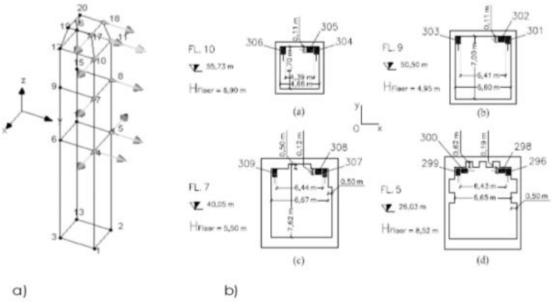

Fig. 3. Localization of the accelerometers on the tower.

During the data elaboration, it was found that accelerometers indicated with 301 and 307 in Figure 3b (floor 7 and 9) were out of order because their measurements were very noisy and no peak appears in their acceleration time-history plots when subjected to an impact force with a hammer.

In Fig. 4 the typical acceleration time-histories recorded by accelerometers 301 and 307 have been compared to the ones recorded by accelerometers 304 and 296. The inspection of Fig. 4 reveals a remarkable difference between the time histories, conceivably related to the different signal-to-noise (S/N) ratio of the four sensors.

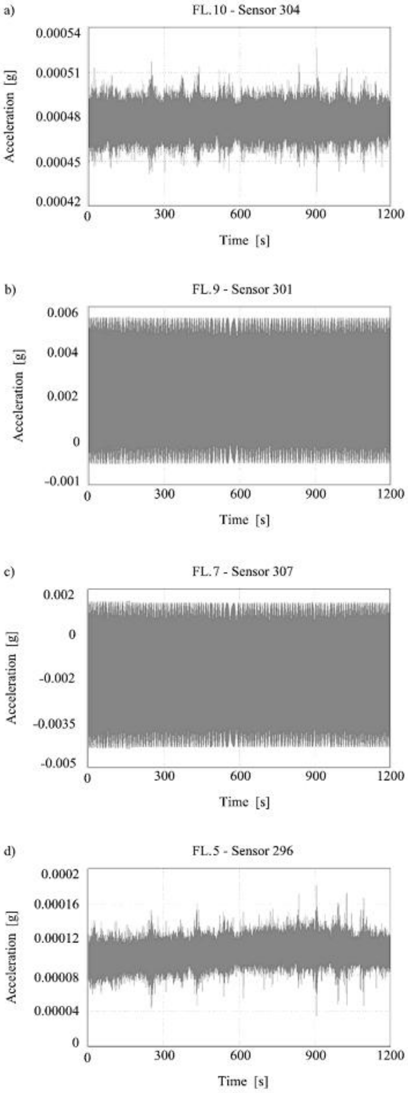

Fig. 4. Comparison between the acceleration time-histories recorded by sensors at different test point of the tower: (a) Floor 10; (b) Floor 9; (c) Floor 7; (d) Floor 5.

As a consequence, the data recorded from sensors 301 and 307 have been neglected from the analysis, i.e. these accelerometers are not be considered in the present work.

3.DATA PROCESSING AND OPERATIONAL MODAL ANALYSIS

The vibration data have been registered in a time interval of 220 minutes at a sample rate of 200 Hz. The signal conversion and the data acquisition were managed by the previously described laptop. The analysis of the recorded data was carried out dividing the time period of 220 minutes of continuous monitoring in eleven intervals of 20 minutes each; a statistical analysis was carried out [14] demonstrating the extreme repeatability of the identified frequencies in the different intervals. The extraction of the modal parameters from ambient vibration data was carried out by using the ARTeMIS Extractor Pro 2010

[13] and, in particular, EFDD, SSI and CC-SSI methods.

In this work the analysis was carried out with reference to one of the interval of length 20 minutes optimizing the characteristics of the used extractor software [13]. In particular, after a deep analysis of the Singular Value Decomposition diagrams (SVD only three channels were selected for the identification analysis. Fig. 5 shows the selected channels and their position on the building.

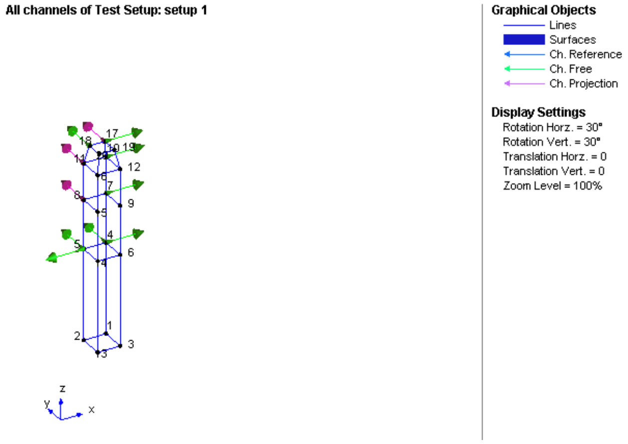

Fig. 5. Accelerometers position and selected channels for identification.

Fig. 6 shows the SVD values of the spectral density matrices carried out in the framework of the EFDD technique, while Figures 7 and 8 show the stabilization diagrams of the state space models obtained by SSI and CC-SSI techniques. It is worth noting that, while the SSI technique is based on an unconditionally linear least squares estimation of the model (through proper processing of the experimental data acquired from the ambient vibration tests), the Crystal Clear SSI technique [13] allows a conditional estimation: it is necessary to specify the maximum number of significant poles (eigenvalues) present in the measurements that should be estimated. This algorithm helps to get clear results leading to cleaner and more stable stabilization diagrams; the CC-SSI estimation feature allows a conditional estimation emphasizing a user defined number of physical modes and suppressing the remaining parts of the information in the data. The estimation algorithm [13] will then focus on the modes having these poles and any less significant noise poles are returned with a natural frequency estimate much higher than the Nyquist frequency, and a damping ratio of 100%, thus reducing their disturbing effects on the physical modes. It is possible to note that the CC-SSI technique (Fig.8) gives a stabilization diagram much more stable than SSI technique (Fig.7) also for high dimension of the estimation matrix (in this case the maximum dimension for SSI and CC_SSI was 150). Moreover, it is evident that SSI (Fig. 7) shows one false frequency around 1.8 Hz; analyzing the SVD diagram this frequency may be removed from the identified frequencies. On the contrary, CC-SSI (Fig.8) doesn't give this false information.

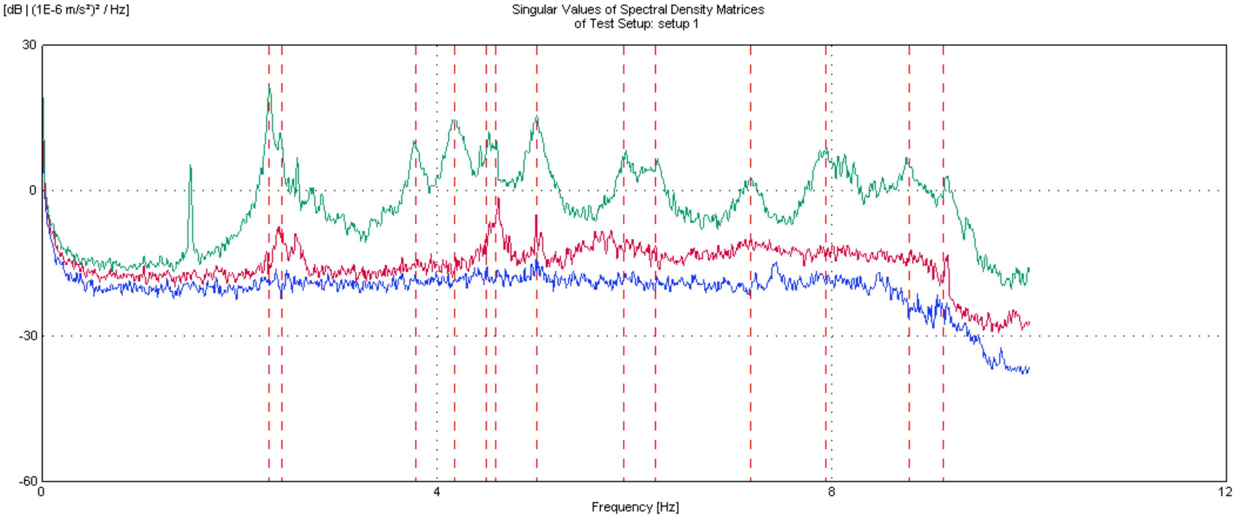

Fig. 6. Singular values of spectral density matrices by EFDD technique.

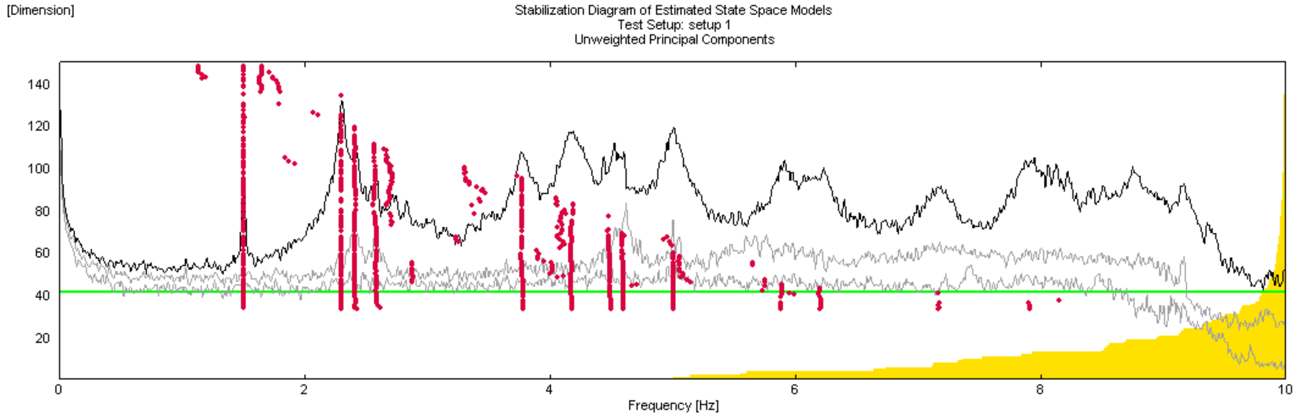

Fig. 7. Stabilization diagram of the state space model by SSI technique.

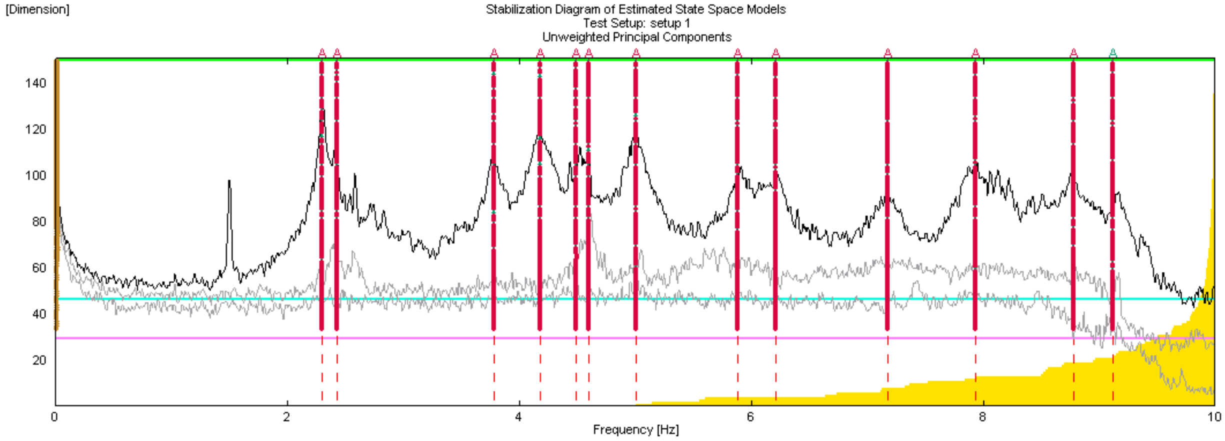

Fig.8. Stabilization diagram of the state space model by CC-SSI technique.

The first 6 frequencies identified for each method are shown in Table 1, demonstrating the consistency of the three methods; this results encourages to use them for a successive calibration of the theoretical model. It is possible to notice that the first two frequencies values are quite close, due to the symmetry of the tower section and, as demonstrated by the following modes identification, these frequencies are related to the first two principal bending modes of the building.

Table 1. First six natural frequencies identified from ambient vibration measurements

	EFDD [Hz]	SSI [Hz]	CC-SSI [Hz]	Mean [Hz]	Standard Deviation [%]
Mode 1	2.303	2.303	2.298	2.301	0.26
Mode 2	2.407	2.440	2.440	2.429	1.90
Mode 3	3.795	3.782	3.781	3.786	0.78
Mode 4	4.178	4.177	4.207	4.187	1.69
Mode 5	4.524	4.489	4.292	4.435	1.25
Mode 6	4.594	4.594	4.610	4.599	0.92

4. MODES IDENTIFICATION

The mode shapes identification has been carried out by introducing some relations between the measured and unmeasured degrees of freedom of the building. In the framework of the ARTeMIS Extractor Pro software [14], in fact, it is possible to define linear combinations of the measured signals (the so-called "Slave Nodes Equations"), which can be very helpful for defining rigid body motions and slave nodes relations. These equations can be used to evaluate the vibrations of the instrumented points, and, as a consequence, to obtain the mode shapes for the entire tower, even though the acquisitions are only available in a few nodes of the geometry. In particular, the data have been analyzed imposing that each floor of the tower is rigid in its plane. In this hypothesis, in fact, the movement of each floor plate can be described imposing mathematical equations between the nodes coordinates in the xy plane [13]. In particular, considering the nodes classification shown in Fig. 3a, equations were applied between the nodes groups (4,5,6,14), (7,8,9,15), (10,11,12,16), (17,18,19,20).

These equations can be used to make the complete geometry move, even though the acquisitions are only available in few nodes of the geometry.

All equations start in the same way as shown below:

Node ("Node Number", "Direction") =… (1)

This equation defines the motion of the node specified by "Node Number" in the direction specified by "Direction". The "Direction" field is a number from 1 to 3: 1 corresponds to X direction, 2 corresponds to Y direction and 3 corresponds to Z direction. The data have been analyzed imposing that each floor of the tower was rigid in its plane. In this hypothesis, in fact, the movement of each floor plate can be described by two displacements and one angle. For the typical floor plate of the tower model the group (generic nodes of a plate depicted in Fig. 9) the plane equations are herein reported.

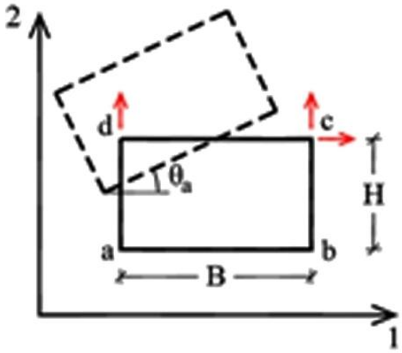

Fig.9. Slave nodes equations for the typical floor plane of the tower.

$$\begin{cases} \text{node}(b,1) = \text{node}(a,1) \\ \text{node}(b,2) = \text{node}(c,2) \\ \text{node}(c,1) = \text{node}(d,1) \\ \text{node}(a,2) = \text{node}(d,2) \\ \text{node}(a,1) = \text{node}(c,1) + \theta_a \cdot H \end{cases} \tag{2}$$

The modes carried out by using the equations (2) are shown in Fig. 10. It is evident that from the identification procedure it is possible to classify mode 1 (y- direction), mode 2 (x- direction), mode 4 (y- direction) and mode 5 (y- direction) as bending modes, and modes 3 and 6 as torsional mode (following the nomenclature of Figure 10 where the number indicates the corresponding frequency). Modes 3 and 6, nevertheless it has been classified as a torsional mode, are not perfectly depicted, probably due to the sensors position on the floor; in fact this position is able to monitor the bending modes, but is surely inaccurate for the complete and correct reconstruction of the torsion modes. This choice, however, was obliged by the impossibility of placing any accelerometer on the opposite side of the tower for the presence of an internal elevator vain and a stair-case.

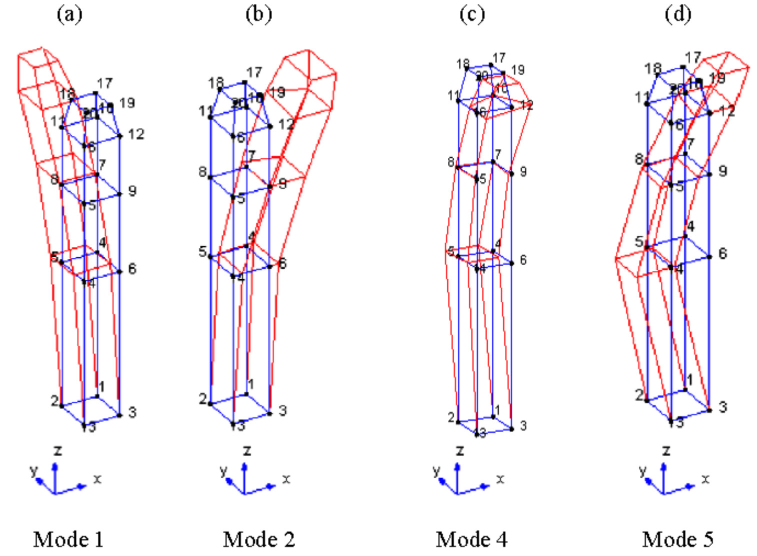

Fig. 10. Vibration modes identified from ambient vibration measurement.

5. CONCLUSIONS

The ambient-vibration based investigations carried out to assess the dynamical behavior of the tower of the Provincial Administration Building of Bari have been presented in this paper. Eleven consecutive ambient vibration tests have been performed for the accurate estimation of the dynamic characteristics, evaluating the statistical repeatability of the results. The response of each accelerometer to the impact of a hammer has been analyzed to check the correct functioning and polarity.

The following conclusions can be drawn from this study:

1. The fundamental mode of the tower, with a natural frequency of about 2.3 Hz, involves dominant bending in E/W direction (that is along the y- axis in the reference system introduced). The coupled motion (about 2.4 Hz) is referred to N/S direction (x- axis).

2. The second couple of bending modes are around 4 Hz and between these two couples of modes there is a torsion mode at a value lower than 4 Hz and immediately higher than the second couple of bending modes. Observing the experimental measurements the torsion mode is not really clear, probably due to the positioning of the accelerometers that, for the same instrumented floors, has been not sufficient to describe the torsional vibrations.

3. A very good agreement was found between the modal estimates obtained from the two classical OMA methods, EFDD and SSI, and the recently implemented CC-SSI method, for each of the consecutive acquisition time intervals; the CC-SSI methods helps to improve the results quality.

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