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Mutual validation between different modal analysis techniques for dynamic identification of the so-called Temple of Minerva Medica, Rome

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Abstract. The dynamic identification by ambient vibration data is widely used to supply information on the global health of structures through the investigation of changes in their modal parameters. It can be used even for verification of the state of damage of structures after hazardous threats, for example seismic activity. Therefore, it can play a crucial role to integrate and support conservation strategies for historic architectural assets. Sometimes, in historic constructions only a limited number of positions are accessible or usable to install sensors, and so modal analysis must be based on data from few measurement points. Moreover, they might not be the optimal positions for the studied structure, so the obtained results would need further verification. In such circumstances, the mutual validation between different modal analysis techniques can be useful to assess the reliability of results. In the present paper a case study of application to the so-called Temple of Minerva Medica, Rome, is described. Ambient vibration data were acquired in four rowing acquisition sessions carried out from July 2016 to July 2017, which is a timespan usable to assess the impact of the recent Central Italy seismic sequence. For problems related to the installation of the scaffolding only few points were available for instruments positioning. A variety of techniques were applied, including FRF, FDD, EFDD, SSI, HVSR and complex modal models. The variance of the modal parameters obtained by each different technique was utilized to provide indications on the reliability of the average values.

1. Introduction

The diagnosis and monitoring of the structural state of damage are crucial issues to a proper planning of restoration, preventive conservation and maintenance interventions of cultural heritage constructions. In particular, in archaeological sites located in areas with high natural hazard, such as in seismic zones, relevant damages may be caused in case of extreme events, such as earthquakes. Unfortunately, this is a quite typical situation in most Italian historic sites, as recent events in Central Italy demonstrated [1]. On the other hand, many Italian archaeological sites are located in historic city centers where also other relevant sources of strong vibration, such as the ones due to urban traffic vehicles, excavation works or other anthropic activities, add to the risk of structural damage [2].

Within this context, methods based on ambient vibration measurements constitute valuable tools to understand the dynamic behavior of a historic building, which is related to its state of damage [3].

A variety of techniques are available to analyze the vibration data, but they are all aimed at the modal identification of the structure, which essentially means at the extraction of the modal parameters that characterize the dynamic behavior of the building. As well known, such parameters can be monitored to give indications on the degradation of the state of health of the structure [4, 5].

In order to have the most accurate and comprehensive understanding of the overall behavior of the studied building, a high number of sensors are usually located on the structure and their positioning is studied so as to maximize the measurable dynamic response [6, 7], e.g. with the help of preliminary numerical estimates of the modal shapes by means of finite element models (FEMs) [8]. Sometimes, though, historic constructions are not completely reachable and only a limited number of positions are accessible or usable to install sensors. In such cases, ambient vibration data from only very few measurement points, possibly not the optimal positions for the studied structure, can be obtained, so results of modal analysis may be very rough and their reliability needs to be verified.

A simple way to provide indications on the reliability of research findings is to validate them through a statistical comparison with other results obtained with more consolidated and accurate data, when such data are available. In other circumstances, a variety of consolidated methods based on different theoretical assumptions can be applied to the same dataset. This idea of mutual validation of data through the application of different methods was fruitfully applied in the present paper to assess the reliability of identified modal frequencies of the so-called Temple of Minerva Medica, an ancient masonry construction located in Rome [9], studied within the framework of the CO.B.RA. project, which focused on the development of advanced technologies and methods for the conservation of cultural heritage assets. For problems related to the positioning of the scaffolding during data acquisitions only limited portions of the monument were accessible and a limited number of measurement points were available for instruments installation. After data acquisition, a variety of modal analysis techniques were applied, both Experimental Modal Analysis (EMA) [10] and Operational Modal Analysis (OMA) [11] techniques, including time-domain [12] and frequency-domain techniques [13], as well as unconventional methods derived from other disciplines that have been proved capable of approximate estimates of the modal frequencies of structures.

2. Modal analysis methods

Modal analysis methods are methods aimed at providing the modal parameters, which are characteristic of the dynamic behavior of the studied building. The main modal parameters are the resonance frequency, the damping ratio and the modal shape associated to each mode of vibration of the studied object. The most used modal parameter for damage detection and monitoring is the natural frequency, which is substantially related to the structural stiffness resulting from the building's shape and from the mechanical properties of the materials it is made of. The basic rationale behind the monitoring of the modal frequencies is that the arising of fractures in the material provokes a loss of stiffness of the entire structure. The more the fracturing processes proceed with time, the more the structure stiffness decays and modal frequencies shift to lower values. Consequently, the modal frequencies can provide indications on the effect of the evolution of the crack pattern of the construction.

The extraction of the modal parameters from a dataset of vibration data acquired by sensors located at measurement points of the structure can be achieved through a variety of techniques. In the following subsections the techniques applied for the estimate of modal frequencies in the present study are illustrated and their characteristics are discussed.

2.1. EMA techniques

The vibration-based analysis techniques aimed at finding the dynamic response of a structure subjected to a known or measurable excitation input are defined as Experimental Modal Analysis (EMA) techniques, because this is generally the case of data acquired in the context of laboratory or field experiments, where vibration input is controlled by test operators. Any external vibration source exciting the structure can be used in these methods, even if some input characteristics (waveform, duration, intensity etc.) may affect accuracy in the dynamic response calculation. The most used EMA techniques are based on frequency domain approaches. In particular, they are commonly based on the implementation of a frequency response function (FRF), i.e. an input-output relationship between two points on a structure as a function of frequency based on the Transmissibility Function H [14]. Since both force and motion have directions associated with them (vector quantities), therefore, an FRF is actually defined in each direction. Moreover, FRFs can be calculated for each couple of signals at input and output points (single-input/single-output or SISO approach). When the input is measured in only one point (single-input), while the response can be measured at several points of the structure (multi-output) FRF calculation can take into account the global behaviour of the structure (SIMO approach), which was the one used in the present work.

2.2. OMA techniques

In contrast to EMA methods, OMA approaches are based on output-only data, i.e. measuring only the response signals of a structure and using the ambient and natural operating forces as unmeasured input. OMA techniques are used instead of classical mobility-based modal analysis for accurate modal identification under actual operating conditions, and in situations where it is practically difficult, inconvenient or even dangerous to artificially excite the structure, such as in the case of many historic buildings.

OMA algorithms generally assume that the input forces are stochastic in nature, so that they can be considered as white-noise signals. This is widely accepted in the case of ambient vibrations of civil engineering structures, which are mainly excited by ambient forces like wind, traffic, urban activities or seismic micro-tremors. One of the most consolidated OMA techniques is the Frequency Domain Decomposition (FDD) [15]. This technique is based on the computation of the Singular Value Decomposition (SVD) of the estimated spectral densities of the measured dynamic response of the structure. After calculating the SVD plots, modes are identified by identifying the peaks in such plots (peak-picking) in the frequency domain. As the FDD technique is based on using a single frequency line from the Fast Fourier Transform (FFT) analysis, the accuracy of the estimated modal frequencies depends on the FFT spectral resolution. In FDD no modal damping is calculated, but in the present paper only the modal frequency will be taken into account.

The Enhanced Frequency Domain Decomposition (EFDD) is a more recent evolution of the FDD with extended potentialities and accuracy [16]. In particular, compared to FDD, the EFDD gives an improved estimate of both the modal frequencies and shapes.

In EFDD, for each mode a power spectral density function, identified around a peak in the SVD, is calculated. After taking it back to the time domain by the Inverse Discrete Fourier Transform (IDFT), the corresponding modal frequency is obtained by computing the number of zero-crossing as a function of time. Besides, the EFDD provides also estimates of the modal damping by the logarithmic decrement of the normalized auto correlation function of the Single Degree Of Freedom (SDOF) corresponding to the identified mode. The SDOF function is estimated using the modal shape determined through the peak-picking method similarly to the FDD. The Subspace Stochastic Identification (SSI) is a time-domain estimator of modal parameters that is based on a difference equation obtained by the raw time-history data. In particular, the SSI method takes advantage a State Space Model that is used to convert higher order problems into 1st order problems [17]. In fact, while estimating at different over-specified model orders, it can be observed that physical modes remain quite constant. Contrarily, spurious modes vary in such conditions so that they can be distinguished using a stabilization diagrams [17].

The use of the stabilization diagram for the extraction of the identified modes implies a high order needed for the identified system. Thus, a very long sequence of nodes is required. An evolution of this method, called Cristal Clear (CCI-SSI), implements the covariance subspace identification [18], through which it is the possible to handle non-stationary data and consequently avoid the choice of too long sequences of measurements. In the following, the CCI-SSI was used in order to obtain clear stabilization diagrams to identify with high accuracy the frequencies of the physical modes.

2.3. HVSR technique

The Horizontal-to-Vertical Spectral Ratio (HVSR) method is applied by calculating the ratio between the amplitude of the Fourier spectra of horizontal and vertical components recorded on a structure. Modes are identified by picking the peaks of the obtained HVSR graphs in the frequency domain.

This method was initially introduced by Nakamura to determine the predominant period of ground motion signals to evaluate site amplification characteristics during earthquakes [19]. Subsequently, it was successfully explored to estimate also the modal frequencies of buildings, on the basis of the simple observation that resonance at lower structural modes (generally the most relevant ones for the overall dynamic behavior of the building) causes vibration amplification in horizontal directions, while the system remains much stiffer and substantially unamplified in the vertical direction. As this is the most common situation of the main bending and torsional modes identified in civil structures, the findings of several studies confirmed the good agreement between the frequencies identified by HVSR and by other most consolidated dynamic identification techniques [20, 21].

3. Experimental application to the so-called temple of Minerva Medica

The above mutual validation approach was applied to the case study of the ambient vibration data acquired on 4th July 2016 at the so-called temple of Minerva Medica. This monument is an ancient ruined building located in the city-center of Rome. Traditionally interpreted as a temple dedicated to Minerva Medica (“Minerva the Doctor”) since 16th century, it was more recently hypothesized to be an ancient nymphaeum part of the Horti Liciniani, but attribution is still discussed [22]. The initial construction could be traced back to the Imperial Rome (early 4th century A.D.), but later several restoration and reconstruction interventions were carried out until 2013 [22].

The main building is a majestic hall with decagonal polylobate plan (diameter of 25 m and overall height originally of 32 m, but currently reduced to only 24 m due to past partial collapses of the dome. Initially, it was entirely built in *opus latericium*, a typical roman technique of that time. After early structural problems arose, it was restored and reinforced through works in *opus mixtum* of tuff bricks and Roman bricks, as well as through the addition of buttresses in the southeast side of the monument, which testify a serious structural weakness in this part of the structure, confirmed by the major historically documented damages concentrated at the south side [22]. In consequence of several historic collapses and reconstructions, the current masonry presents quite heterogeneous materials and irregular shapes.

3.1. Ambient vibration acquisitions and analysis

The vibration data were collected by the use of 5 digital recorders positioned at the measurement points depicted in figures 1 and 2.

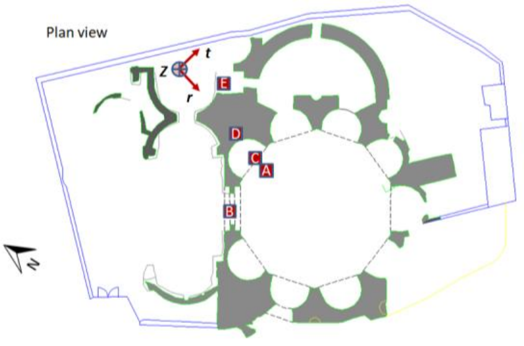

Figure 1. Plan view of the monument with positions of instruments (in red squares).

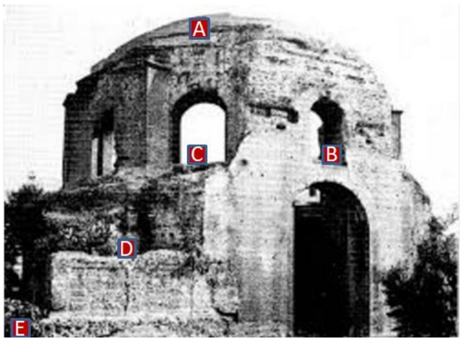

Figure 2. Measurement points on the main façade (view from North).

Figure 3. Installation of measurement point A at the dome curb on the north side.

Figure 4. Instrumentation setup: position C.

Each digital recorder was equipped with a triaxial velocimeters, whose time synchronization is guaranteed by a GPS antenna. Data were acquired for 20 minutes at a sampling frequency of 200 Hz, as in previous similar studies [23].

According to the instruments setup procedure, the digital recorders were simply laid on the horizontal surfaces available and reachable by proper scaffoldings (figures 3 and 4). Consequently, they could be located only at the two reachable windows (positions B and C), at the dome curb on the north side (A), on the base wall (D) and on the ground foundation (E). Measurement at E was adopted as input signal for FRF calculations, as the ground vibration due to tram and train passages very close to the monument was assumed as the main responsible of dynamic excitation to the structure. This assumption was taken after verifying that vibration intensity at E revealed strong peaks in correspondence of tram and train passages. All other positions (A, B, C and D) were taken as output signal (SIMO approach). The HVSR was calculated as the average response of A, C and B, as E and D substantially gave the ground response. Both FRF and HVSR were calculated in north (N) and east (E) directions.

4. Results

The modal frequencies for the first five modes covering a frequency range of 0-5 Hz were considered in the analyses. Figure 5 illustrates the results obtained by the application of FRF with SIMO approach between 0 and 5 Hz.

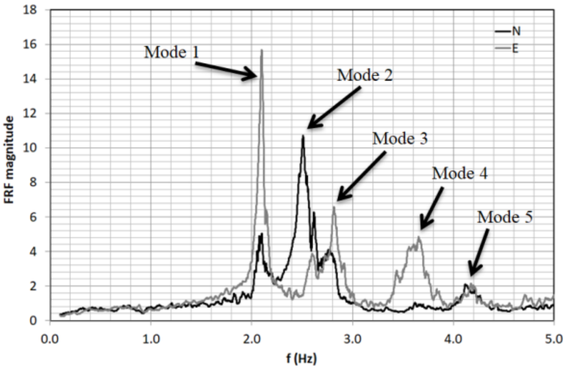

Figure 5. Modal frequencies identified by FRF magnitude peaks in North (N) and East (E) directions.

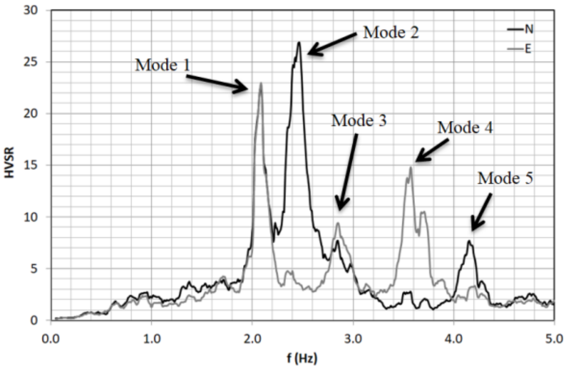

Figure 6. Modal frequencies identified by peaks in the Horizontal-to-Vertical Spectral Ratio (HVSR) in North (N) and East (E) directions.

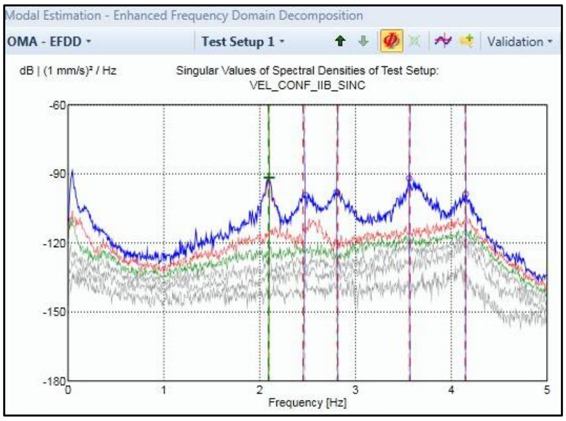

Figure 7. Modal frequencies by Enhanced Frequency Domain Decomposition (EFDD)

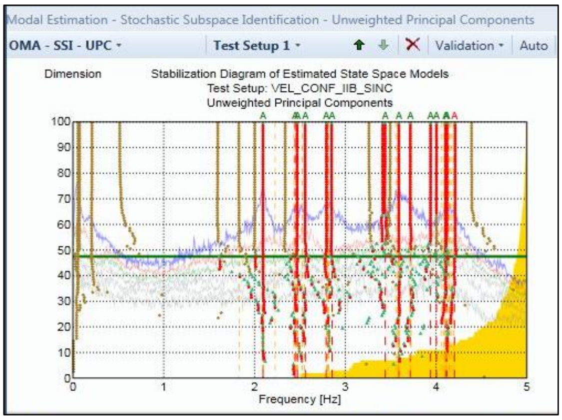

Figure 8. Modal frequencies by Cristal Clear Stochastic Subspace Identification (CC-SSI).

It shows evident peaks in North (N) and East (E) directions, which clearly identify the first f modes. Similarly, figure 6 illustrates the peaks of the HVSR computed by averaging the curves at A, B and C positions. As for the OMA techniques, all the applied methods provided very similar modal frequencies. In particular, the identification of modes by EFDD through the analysis of the SVD is depicted in the figure 7, while the modes found by CC-SSI through the analysis of the stabilization diagram is shown in figure 8. In order to quantify the results convergence some statistical parameters were used. In particular, in the following, the modal frequencies calculated from each technique were compared through their standard deviation (SD) and their coefficient of variation (CV), which is defined as the percentage ratio of SD to the corresponding average frequency value. Moreover, In order to take into account that OMA techniques are not strictly independent methods, as they are based on similar assumptions, especially about the unknown input, the frequencies obtained by OMA methods were averaged and correlated separately to FRF and HVSR results, respectively.

On the basis of the linear regression obtained in these correlations a mutual evaluation of the validity of the results was carried out. In particular, the higher the correlation of the linear regression and the closer the correlation equation to the identity line, the more the results can be considered validated. All the obtained results are summarized in table 1, which shows the modal frequencies extracted with all the applied methods, along with some basic statistics (average, standard deviation SD, coefficient of variation CV).

Table 1. Modal frequencies calculated with all applied modal analysis technique and basic statistics (average, standard deviation SD, coefficient of variation CV) for the first five modes.

	Modal frequencies (Hz) by analysis technique							Statistics		
Mode	FDD	EFDD	CC-SSI	HVSR (N)	HVSR (E)	FRF (N)	FRF (E)	average	SD	CV
1	2.100	2.092	2.094	2.090	2.090	2.097	2.090	2.093	0.004	0.19%
2	2.476	2.454	2.473	2.470	--	2.506	--	2.476	0.019	0.76%
3	2.803	2.816	2.789	2.814	2.850	2.777	2.812	2.809	0.023	0.83%
4	3.555	3.568	3.591	--	3.570	--	3.662	3.589	0.043	1.19%
5	4.150	4.147	4.120	4.160	--	4.120	4.178	4.146	0.023	0.55%

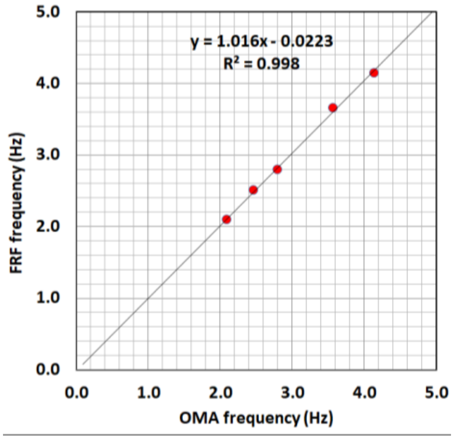

Figure 9. Correlation between OMA and FRF results.

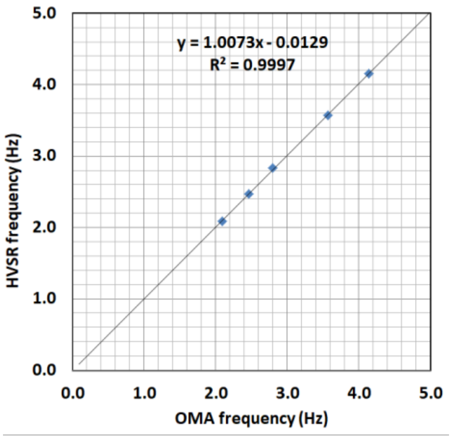

Figure 10. Correlation between OMA and HVSR results.

The figures 9 and 10 illustrate the correlation found of the average OMA to the average FRF and HVSR frequencies, respectively. Both correlations showed very high coefficients of determination R^2 with linear regressions very close to the identity line expressed by the relation y = x. These statistical comparisons substantially indicated that OMA, FRF and HVSR provided almost identical outcomes, which offers a solid basis for mutual validation of results.

5. Conclusions

The present work was conducted with the aim to assess the validity of the modal frequencies obtained by ambient vibration data acquired at very few measurement points of the so-called temple of Minerva Medica. The relevance, accuracy and validity of the provided modal frequencies of a monument are provided by the high reliability of the modal parameters for diagnostic and monitoring of the structure's state of damage. To such purposed a variety of modal analysis techniques were applied to the recorded dataset, namely OMA, FRF and HVSR methods, which are based on different theoretical assumptions. The results obtained through the applied methods were compared by basic statistical analysis for mutual validation. According to such statistical comparison, a very good agreement was found for the frequencies computed through all above methods, which substantially provided almost identical outcomes. Consequently, a solid basis for mutual validation of the results could be demonstrated, corroborating the reliability of the obtained findings.

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