GEOFIZIKA VOL. 28 2011

Original scientific paper
UDC 550.8.013

Operational modal analysis for the characterization of heritage structures

Carlo Rainieri and Giovanni Fabbrocino

Structural and Geotechnical Dynamics Laboratory StreGa
Department of S.A.V.A., University of Molise, Campobasso, Italy

Received 11 December 2010, in final form 17 May 2011

Assessing and reducing the seismic risks associated with historical structures require an appropriate knowledge of structural behaviour and characteristics, as suggested by recent national and international guidelines concerning cultural heritage. However, historical structures are characterised by a high level of uncertainty, which affects material properties and structural schemes and is related to deterioration processes or previous interventions and structural modifications. The level of knowledge can be increased by experimentally evaluating a structure's dynamic properties, and the resultant data can be used to refine and update numerical models that are representative of the real structural behaviour. Moreover, the periodic monitoring of relevant parameters can help identify eventual deterioration phenomena. Thus, dynamic tests, in conjunction with model updating, are becoming reliable tools for non-destructively assessing historical structures. In this article, a brief discussion of the basic principles of dynamic identification under operational conditions is presented. Two tests with historical structures are then presented, and the main results are reported. The high performance of operational modal analysis techniques and the interesting opportunities these techniques provide for the structural assessment of historical structures are discussed.

Keywords: heritage structures, ambient vibration tests, operational modal analysis

1. Introduction

Italy and south-eastern Europe are characterised by their cultural heritage, which is spread out over their territories; however, they are also affected by high seismic risks. Thus, effective measures must be taken to protect structures and mitigate losses due to seismic events. This need for protection affects not only ordinary structures in terms of safety but also historical structures in terms of mitigating losses to the arts and unique artefacts.

From a structural engineering perspective, this objective can be reached by increasing the knowledge of structural behaviour, in particular, knowledge related to dynamic loads.

However, this can be particularly difficult with historical structures in which a large number of uncertainties affect material properties and structural schemes; as a result, reliable models are difficult, if not impossible, to identify.

The theme of assessing and reducing the seismic risks associated with historical structures is becoming increasingly important due to the large number of potentially vulnerable heritage structures. The effects of recent earthquakes (Umbria-Marche, 1997; Molise, 2002; L'Aquila, 2009) on historical structures have determined that these issues are crucial, and various codes and guidelines have been produced.

In seismic codes, an increasing amount of attention has been paid to historical structures because they share some common characteristics with existing structures and also exhibit some peculiar aspects that prevent them from being treated according to current building practices without preliminary evaluations of their effects. Thus, in the current Italian seismic code (DPCM-NTC2008, 2010; Consiglio Superiore dei Lavori Pubblici, 2008), specific recommendations related to interventions for heritage structures are reported.

The guidelines for assessing and reducing the seismic risks associated with historical structures provide general principles and specific suggestions depending on the structural typology. As a general rule, interventions must be as limited as possible, and they must be based on increasing levels of knowledge. The methodological path is summarised in Figure 1. Limited or exten-

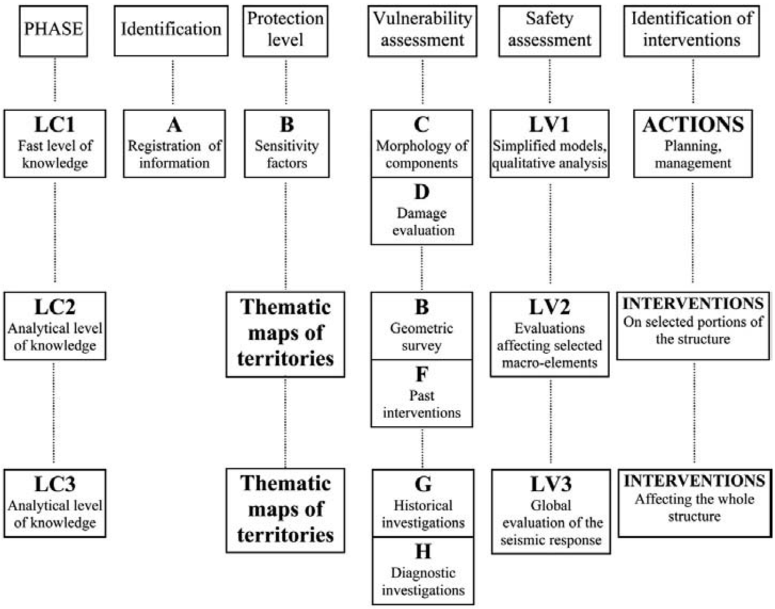

Figure 1. The methodological path for interventions on historical structures.

sive interventions are possible, but a high level of confidence in the knowledge of a structure's behaviour is required.

As a consequence, a number of tests and surveys must be conducted to define a representative model of the behaviour of a structure or to demonstrate that a global approach cannot be pursued. In the latter case, simplified assumptions on limited parts of the structural system can be used to support decisions related to the extension and nature of interventions. However, destructive tests must be limited in number due to the valuable characteristics of historical structures. Conversely, non-destructive and non-invasive tests are preferred.

Ambient vibration tests in conjunction with model updating techniques can be considered to be an effective non-destructive tool for assessing the dynamic behaviour of existing and, in particular, historical structures. Moreover, with repeated tests, they can be helpful in evaluating the health of structures. In fact, modal-based structural health monitoring is becoming a reliable and widely accepted technology for detecting structural damage.

In this article, two dynamic tests of historical structures are described, and the main results are reported. Modal identification is based on operational modal analysis (OMA) techniques. The fundamentals, potentialities and limitations of such methods are also briefly reviewed.

2. Operational modal analysis: a review

In recent decades, new and powerful numerical methods for static and dynamic analyses and designs of civil structures have been developed. In particular, the finite element (FE) method, together with the rapid development of computer technology, has provided structural designers with excellent analytical tools capable of accurately simulating structural behaviour.

However, the development of new high-performance materials and the increasing complexity of designed structures have led engineers to request appropriate experimental procedures for identifying the most relevant structural properties. This data can then be used to support the calibration and validation of numerical models.

Dynamic properties computed with the FE method can differ from the actual dynamic properties of a structure for several reasons. First, FE analysis is based on a discretisation of a global model, and the displacement fields are approximated by predefined shape functions within each element; moreover, some simplified modelling assumptions, such as mass lumping or rigid diaphragms, can cause scattering with respect to the actual behaviour. Damping is another source of uncertainty. Finally, the actual geometry of the structure can be somewhat different from that of the model.

Ageing and structural deterioration are also crucial issues in structural design and maintenance. The regular identification of modal parameters can play a relevant role in the development of effective structural health monitoring systems.

Over the last thirty years, these circumstances have led civil engineers to exploit a number of techniques developed in the fields of system identification and experimental modal analysis. These techniques first referred to electrical engineering applications, but they progressively spread to other fields including automotive, aerospace and civil engineering. With input-output modal identification procedures, such techniques enable the experimental identification of the dynamic properties of structures.

Traditional experimental modal analysis (EMA), however, suffers from several limitations, as described below.

– It requires artificial excitation to evaluate frequency response functions (FRF) or impulse response functions (IRF). In some cases, such as civil structures, providing adequate excitation is difficult if not impossible.

– Operational conditions are often different from those adopted in tests because traditional EMA is conducted in a laboratory environment.

– The boundary conditions are simulated because tests are usually conducted in a laboratory environment on components instead of with complete systems.

As a consequence, since the early 1990s, the civil engineering community has paid an increasing amount of attention to OMA, with applications for several structures, including buildings, bridges and offshore platforms.

OMA uses structural response measurements from ambient excitation to extract modal characteristics. Thus, it is also called ambient, natural-excitation or output-only modal analysis.

Compared to traditional EMA, OMA is attractive due to a number of advantages:

– it is faster and cheaper than EMA;

– no excitation equipment or boundary condition simulations are needed;

– it does not interfere with the normal use of the structure;

– it enables the identification of modal parameters that are representative of the entire system under actual service conditions; and

– OMA also can be used for vibration-based structural health monitoring and to detect damage in structures (Rainieri, 2008).

For historical structures, output-only techniques are preferred (Gentile, 2005), because artificial excitation often presents problems for test execution and input control and environmental loads are always present. Moreover, they imply minimum interference with the normal use of the structure.

The identified modal parameters, which are representative of the structural behaviour under operational conditions, can be used to validate or update FE models (Jùlio et al., 2008); moreover, changes in the modal parameters over time can be correlated to structural modifications or damage (Doebling et al., 1996).

Finally, combining numerical models and experimental measurements offers interesting opportunities for the vibration and seismic protection of strategic and historical structures. Updated analytical models can be used to effectively evaluate the seismic risks associated with structures and to check the performance of these structures following a seismic event.

Although most operational modal analysis techniques are derived from traditional EMA procedures, the main difference is related to the basic assumptions about the inputs. In fact, EMA procedures are developed in a deterministic framework, while OMA methods are based on random responses and, therefore, a stochastic approach. Thus, many OMA techniques can be seen as the stochastic counterparts of the deterministic methods used in classical EMA, despite the availability of new hybrid deterministic-stochastic techniques (Van Overschee and De Moor, 1994; Fassois, 2001).

OMA is based on the assumption that inputs are a Gaussian white noise, characterised by a flat spectrum in the frequency range of interest. As a consequence, modes are uniformly excited and extracted using the appropriate procedures. However, this assumption leads to some drawbacks:

– modal participation factors cannot be computed; and

– reliably extracting modal parameters can be difficult in the presence of spurious harmonics near the natural frequencies of a structure.

The assumption about the nature of inputs has another consequence related to the classification of the methods. In both OMA and EMA, the modal identification procedures can be classified as frequency domain or time domain techniques, depending on the domain in which they work.

Other common distinctions exist between global and local methods and between single degree of freedom (SDOF) and multiple degree of freedom (MDOF) methods (Heylen et al., 2002). However, while EMA techniques can be classified according to the number of inputs and outputs (Single Input Single Output, Single Input Multiple Output, Multiple Input Single Output, Multiple Input Multiple Output), OMA algorithms are always of the MIMO-type because of the aforementioned assumption about input.

Regardless of these differences, experimental modal analysis is always based on the following three steps:

– test planning and execution, including the proper location of sensors and, eventually, actuators, the selection of data acquisition parameters and the eventual application of external excitation;

– data processing and modal parameter extraction; and

– validation of the modal model.

Once the modal model has been identified, it can be used for the following purposes:

– troubleshooting, if the identified vibration properties are used to determine the cause of problems often encountered in real life, such as excessive noise or vibrations;

– model updating, if the experimental modal properties are used to enhance an FE model of a structure to make it adhere more closely to the actual behaviour of a structure; this is particularly useful for historical or heritage structures characterised by complex structural systems and uncertain material properties;

– structural modification and sensitivity analysis to evaluate the effect of changes on the dynamics of a structure without actual modifications;

– structural health monitoring and damage detection by comparing modal parameters from the current state of a structure with those at a reference state to obtain information about the presence, location and severity of damage;

– performance evaluation, if modal parameters and mode shapes are used to evaluate the dynamic performance of a system; and

– force identification starting with only structural response measurements.

Operational modal analysis techniques are based on the following assumptions:

– linearity: the response of a system to a certain combination of inputs is equal to the same combination of corresponding outputs;

– stationarity: the dynamic characteristics of a structure do not change over time, and the coefficients of the differential equations are constant with respect to time; and

– observability: the test setup must be defined to enable measurements of the dynamic characteristics of interest; for instance, nodal points must be avoided to detect a certain mode.

OMA techniques can be classified into two main groups of parametric and non-parametric methods; if a model is fitted to data, the technique is parametric. These techniques are more complex and computationally demanding, and they usually perform better than the faster and easier non-parametric techniques, which, however, are preferred for initial insight into the identification problem.

The most undemanding method for output-only modal parameter identification is the basic frequency domain (BFD) technique (Bendat and Piersol, 1993), also called the Peak-Picking method, because the identification of eigenfrequencies is based on peak picking in the power spectrum plots. However, this method can lead to erroneous results if the basic assumptions of low damping and well-separated frequencies are not fulfilled. In fact, the method identifies the operational deflection shapes, which are the superpositions of multiple modes for closely spaced modes.

The singular value decomposition (SVD) of the power spectral density (PSD) matrix overcomes these shortcomings and leads to the frequency domain decomposition (FDD) method (Brincker et al., 2000), which is capable of detecting mode-multiplicity. However, both of these techniques are non-parametric methods because the modal parameters are obtained without fitting a mathematical model to the measured data.

Among the parametric methods, the least square complex exponential, the eigensystem realization algorithm, the ARMAV models, the stochastic subspace methods and the maximum likelihood frequency domain method can be mentioned (Zhang et al., 2005). The least square complex exponential and eigensystem realization algorithm are used, in the context of NExT techniques, to extract modal parameters from the auto- and cross-correlations of time signals.

Dynamic systems can also be modelled with ARMAV models (Andersen, 1997). In the stochastic subspace identification method, a stochastic state space model is identified directly from measured output data (Van Overschee and De Moor, 1996).

The frequency domain maximum likelihood approach, which was developed for frequency response functions, has been extended to extract modal parameters from output spectra (Hermans et al., 1998).

Details about the mentioned techniques can be found in the literature. A comprehensive review of operational modal analysis procedures can be found in Rainieri (2008), Zhang et al. (2005) and Rainieri and Fabbrocino (2008). In the following sections, some applications of OMA to historical structures are described, together with a theoretical background of the operational modal analysis technique adopted for data processing. Such a method has been implemented in a specific software program developed in the LabView environment (Rainieri et al., 2007).

3. The modal parameter identification technique: theoretical background

The modal parameters of tested structures are obtained from output-only measurements using the FDD technique (Brincker et al., 2000).

This technique is an extension of the BFD method. The theoretical basis can be summarised as follows.

The relationship between the input $x(t)$ and the output $y(t)$ can be written in the following form (Brincker et al., 2000):

$$[G_{yy}(\omega)] = [H(\omega)]^*[G_{xx}(\omega)]\,[H(\omega)]^T \tag{1}$$

where $[G_{xx}(\omega)]$ is the $r \times r$ input PSD matrix; r is the number of inputs; $[G_{yy}(\omega)]$ is the $m \times m$ output PSD matrix; m is the number of outputs; $[H(\omega)]$ is the $m \times r$ FRF matrix; and the superscripts * and ^{T} denote complex conjugate and transpose, respectively.

The FRF matrix can be expressed in a typical partial fraction form, which is used in classical modal analysis, in terms of poles, λ, and residues, $[R]$:

$$[H(\omega)] = \frac{[Y(\omega)]}{[X(\omega)]} = \sum_{k=1}^{n}\left(\frac{[R_k]}{j\omega-\lambda_k} + \frac{[R_k]^*}{j\omega-\lambda_k^*}\right) \tag{2}$$

with

$$\lambda_k = -\sigma_k + j\,\omega_{dk} \tag{3}$$

where n is the number of modes; λ_k is the pole of the k^{th} mode; σ_k is the modal damping decay constant; and ω_{dk} is the damped natural frequency of the k^{th} mode. $[R_k]$ is the residue, and it is given by

$$[R_k] = \{\phi_k\}\{\gamma_k\}^T \tag{4}$$

where $\{\phi_k\}$ is the mode shape vector, and $\{\gamma_k\}$ is the modal participation vector.

Therefore, combining eq. (1) and (2) and assuming that the input is random in both time and space and has a zero mean white noise distribution (i.e., the PSD is constant: $[G_{xx}(\omega)] = [C]$), the output PSD matrix can be written as

$$[G_{yy}(\omega)] = \sum_{k=1}^{n}\sum_{s=1}^{n}\left[\frac{[R_k]}{j\omega-\lambda_k} + \frac{[R_k]^*}{j\omega-\lambda_k^*}\right][C]\left[\frac{[R_s]}{j\omega-\lambda_s} + \frac{[R_s]^*}{j\omega-\lambda_s^*}\right]^H \tag{5}$$

Using the Heaviside partial fraction theorem for polynomial expansions, the following result can be obtained:

$$[G_{yy}(\omega)] = \sum_{k=1}^{n}\left(\frac{[A_k]}{j\omega-\lambda_k} + \frac{[A_k]^*}{j\omega-\lambda_k^*} + \frac{[B_k]}{-j\omega-\lambda_k} + \frac{[B_k]^*}{-j\omega-\lambda_k^*}\right) \tag{6}$$

This is the pole-residue form of the output PSD matrix. $[A_k]$ is the k^{th} residue matrix of the output PSD; it is an $m \times m$ hermitian matrix given by

$$[A_k] = [R_k][C]\sum_{s=1}^{n}\left(\frac{[R_s]^H}{-\lambda_k-\lambda_s^*} + \frac{[R_s]^T}{-\lambda_k-\lambda_s}\right) \tag{7}$$

If only the k^{th} mode is considered, the following contribution is obtained:

$$[A_k] = \frac{[R_k][C][R_k]^H}{2\sigma_k} \tag{8}$$

This term can become dominant if the damping is low, and a residue proportional to the mode shape vector can be obtained as follows:

$$[A_k] \propto [R_k]\,[C]\,[R_k]^H = \{\phi_k\}\{\gamma_k\}^T[C]\{\gamma_k\}\{\phi_k\}^T = d_k\{\phi_k\}\{\phi_k\}^T \tag{9}$$

where d_k is a scaling factor for the k^{th} mode.

For a lightly damped system in which the contribution of the modes at a particular frequency is limited to a finite number (usually one or two), the response spectral density matrix can be written in the following final form:

$$[G_{yy}(w)] = \sum_{k \in Sub(\omega)} \left(\frac{d_k \{\phi_k\}\{\phi_k\}^T}{j\omega - \lambda_k} + \frac{d_k^* \{\phi_k\}^* \{\phi_k\}^{*T}}{j\omega - \lambda_k^*} \right) \tag{10}$$

where $k \in Sub(\omega)$ is the set of contributing modes at the considered frequency.

The SVD of the output PSD matrix known at discrete frequencies $\omega = \omega_i$ gives

$$[\hat{G}_{yy}(j\omega_i)] = [U]_i \, [S]_i \, [U]_i^H \tag{11}$$

where the matrix $[U]_i$ is a unitary matrix holding the singular vector $\{u_{ij}\}$, and $[S]_i$ is a diagonal matrix holding the scalar singular values s_{ij}. Near a peak corresponding to the k^{th} mode in the spectrum, this mode will be dominant. If only the k^{th} mode is dominant, only one term in eq. (10) exists, and the PSD matrix approximates to a rank one matrix:

$$\hat{G}_{yy}(j\omega_i) = s_i \{u_{i1}\} \{u_{i1}\}^H \; \omega_i \to \omega_k \tag{12}$$

In such a case, therefore, the first singular vector $\{u_{i1}\}$ represents an estimate of the mode shape:

$$\{\hat{\phi}\} = \{u_{i1}\} \tag{13}$$

and the corresponding singular value belongs to the auto power spectral density function of the SDOF system corresponding to the mode of interest. In the case of repeated modes, the PSD matrix rank is equal to the multiplicity number of the modes. The auto power spectral density function of the corresponding SDOF system is identified around the peak of the singular value plot by comparing the mode shape estimate $\{\hat{\phi}\}$ with the singular vectors associated with the frequency lines around the peak. Every line characterised by a singular vector that gives a MAC value $\{\hat{\phi}\}$ higher than an appropriate user-defined MAC Rejection Level belongs to the SDOF PSD function (Gade et al., 2005).

This equivalent SDOF PSD function is used to obtain estimates of the damping ratios, and natural frequencies independent of the frequency resolution of the spectra (Gade et al., 2005). In fact, the SDOF PSD function is restored in the time domain through an Inverse FFT, yielding an approximated correlation function of the equivalent SDOF system. From the free decay function of the SDOF system, the damping ratio can be calculated with the logarithmic decrement technique. A similar procedure is adopted to extract the natural frequencies through a linear regression on the zero crossing times of the equivalent SDOF system correlation function, accounting for the relationship between the damped and undamped natural frequencies.

4. The Tower of the Nations

This section describes the modal identification tests conducted on the Tower of the Nations in Naples (Siola, 1990) to increase the level of knowledge of the structure's behaviour for the design of restoration and seismic upgrading interventions, which were required to account for the valuable characteristics of the structure and were, therefore, as limited as possible.

The Tower of the Nations (Figure 2) is one of the most important and representative structures in the Mostra D'Oltremare area in Naples. It is a reinforced concrete building characterised by two opposite blind and two completely transparent façades. Elevator shafts and stairs are located in the centre of the building. Apart from the first, second and third floors, the remainder of the building was built to allow occupants to see from floor to floor (Figure 3a).

The dynamic response of the structure was measured at the fourth and fifth levels and on the roof. The roof and the fifth level were instrumented in two corners. In each corner, two force balance accelerometers were placed. An-

Figure 2. The Tower of the Nations (Naples) at completion, 1940.

(a)

(b)

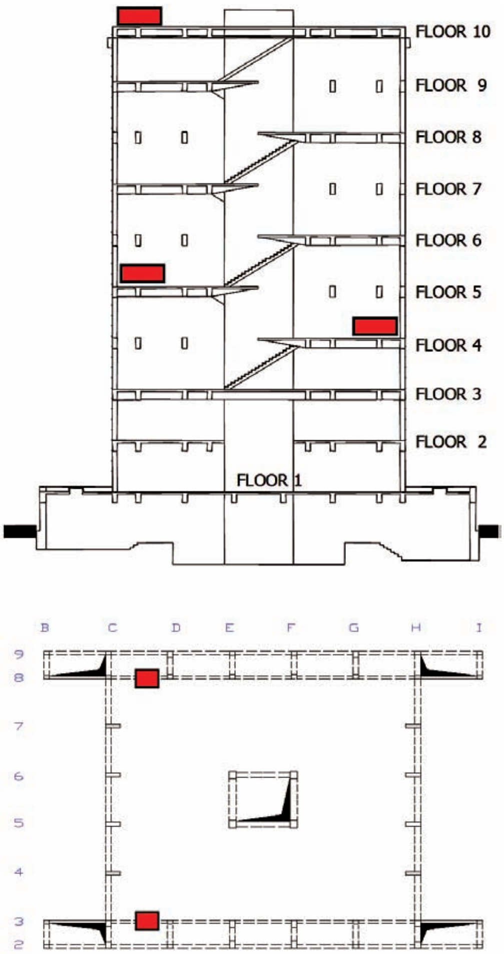

Figure 3. The Tower of the Nations – test layout. Cross section of the building (a) and plan view of the top floor (b).

other couple of accelerometers was placed on the fourth floor. Figure 3 shows the adopted testing layout.

The ten accelerometers were placed directly in contact with the concrete slab and parallel to the main directions of the building to obtain both the translational and torsional modes of the structure. The sensors had a bandwidth (–3 dB) of approximately 200 Hz (starting from DC) at 1 g and a high dynamic range (140 dB). The full-scale range could be set by the user and could vary from ±4 g (0.625 V/g as sensitivity) to ±0.25 g (10 V/g as sensitivity). Sensitivity values were related to a single-ended configuration and a ±2.5 V output.

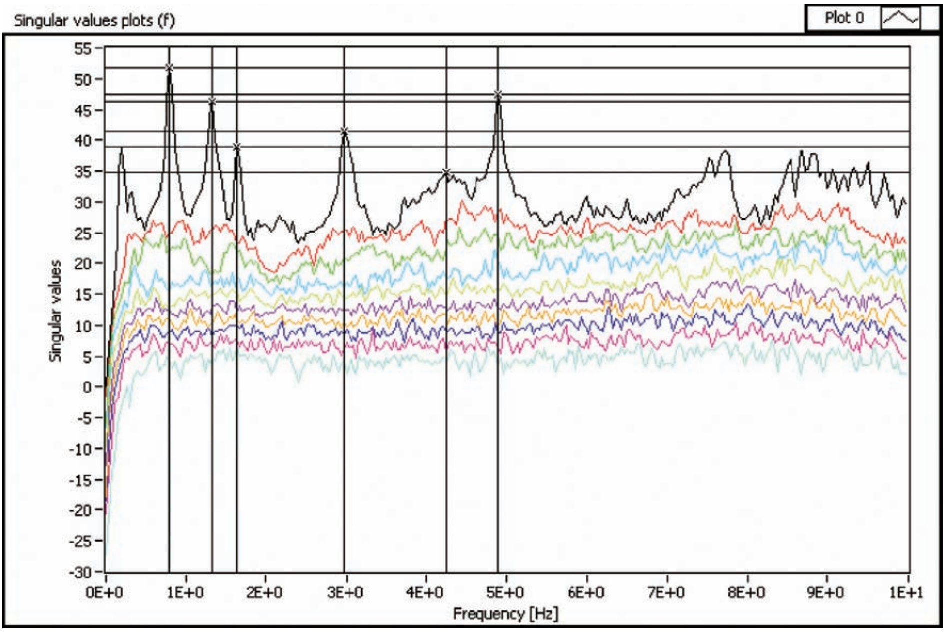

Figure 4. The Tower of the Nations – singular value plots.

In this application, a full-scale range of $\pm 0.25\ g$ was adopted in compliance with the low level of acceleration induced in the structure by ambient noise. A digital recorder, characterised by a 24-bit DSP, an analogue anti-aliasing filter and a high dynamic range (> 114 dB at 200 sps), was used for data acquisition. The accelerometers and the recorder were linked with a 24 AWG cable with individually shielded twisted pairs. After a first, shorter trial record, two records of the structural response were collected. They were long enough (25 and 40 minutes) to ensure a large number of averages in the spectrum computations.

Prior to processing, data were standardised to check the quality of measurements (e.g., the absence of clipping and drop-out) and to ensure that the data were approximately normally distributed. Moreover, the records were pre-treated to remove means and trends (Bendat and Piersol, 1986). The data were approximately normally distributed, as indicated by kurtosis index values of approximately 3.

Modal parameter identification was conducted according to the FDD approach. Spectra were computed using a Hanning window to avoid leakage, with a 66% overlap.

Figure 4 presents the singular value plots, and the peaks relative to the first six modes are highlighted. The modal identification results in terms of natural frequencies, damping ratios and mode shapes are reported in Table 1. The damping ratios for the last three modes are not provided due to the difficulty of obtaining estimates with this technique for all the considered records.

Table 1. The Tower of the Nations – results of output-only modal identification.

Mode number	Type	Natural frequency (Hz)	Damping ratio (%)
1	Translation (open side)	0.80	0.8
2	Translation (blind side)	1.33	1.1
3	Torsion	1.66	0.9
4	Translation (open side)	2.96	N.A.
5	Translation (blind side)	4.23	N.A.
6	Torsion	4.90	N.A.

The first and fourth modes are translational modes parallel to the open side of the building; the second and fifth modes are translational modes parallel to the blind side; and the third and sixth modes are torsional modes.

The estimated mode shapes were checked with complexity plots. As shown in Figure 5, all modes were normal or nearly normal (see, for instance, the fifth and sixth modes, which are weakly excited).

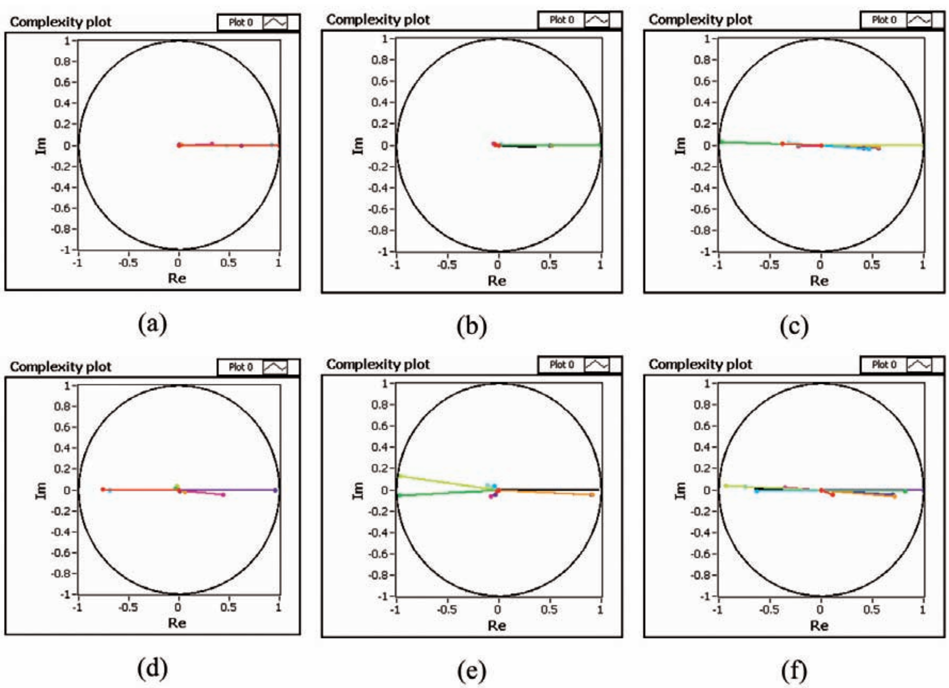

Figure 5. The Tower of the Nations – complexity plots. Mode #1 (a), #2 (b), #3 (c), #4 (d), #5 (e) and #6 (f).

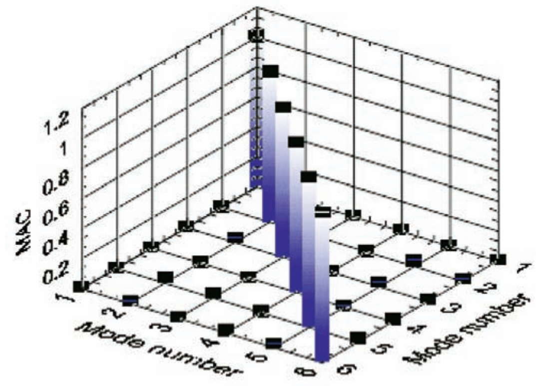

Figure 6. The Tower of the Nations – AutoMAC matrix.

Figure 6 shows the AutoMAC matrix and indicates the effectiveness of the adopted test layout for distinguishing the different modes. The values along the main diagonal are equal to 1, and those in the remainder of the matrix are near 0.

These results were used for a model updating application; more details about model calibration based on modal identification results can be found elsewhere (Rainieri, 2008). In this context, effective techniques for model refinement were obtained by comparing the measured modal properties with the results of several FE models. The primary role of masonry infills in determining the dynamic behaviour of the structure is highlighted by the correlation between the numerical and experimental results. Moreover, indirect estimates of the elastic properties of the concrete and tuff masonry were obtained, together with suggestions about proper modelling of the interaction between the Tower and the surrounding basement. Thus, the primary role played by structural identification in enhancing the level of knowledge about historical structures through non-invasive interventions was demonstrated.

5. The bell tower of Santa Maria del Carmine

In this section, tests of an ancient masonry bell tower located in the surrounding area of Naples are described. The structure is characterised by six levels above ground. It is approximately 60 m tall and is characterised by a rectangular cross section to a height of approximately 41 m. This first section is a masonry structure composed of Neapolitan yellow tuff. The remainder of the structure has an octagonal cross section and is composed of brick masonry walls.

Figure 7 shows a picture of the bell tower. The tower is not separated from the surrounding structures. Thus, one of the objectives of the dynamic tests was to study the level of interaction with the nearby structures through comparisons and correlations between numerical and experimental results (Ceroni et al., 2007b).

A number of tests were conducted to investigate the mechanical properties of the materials (Ceroni et al., 2007a; Ceroni et al., 2007b) to be used in the numerical model of the structure. Moreover, some dynamic tests were conducted to refine the FE model. Attention was focused on the first two mode shapes because of their importance in linear and non-linear static analyses (Ceroni et al., 2007b).

The sensors used were force balance accelerometers similar to those used to test the Tower of the Nations. A 30-minute record was acquired and processed to extract the modal properties of the structure.

The first two modes obtained with output-only measurements and the FDD technique were bending modes characterised by the natural frequencies of 0.70 Hz and 0.76 Hz. Figure 8 shows the singular value plots obtained from the time histories, which were courteously provided to the authors.

Figure 7. The bell tower of Santa Maria del Carmine (Naples) (Courtesy of F. Ceroni).

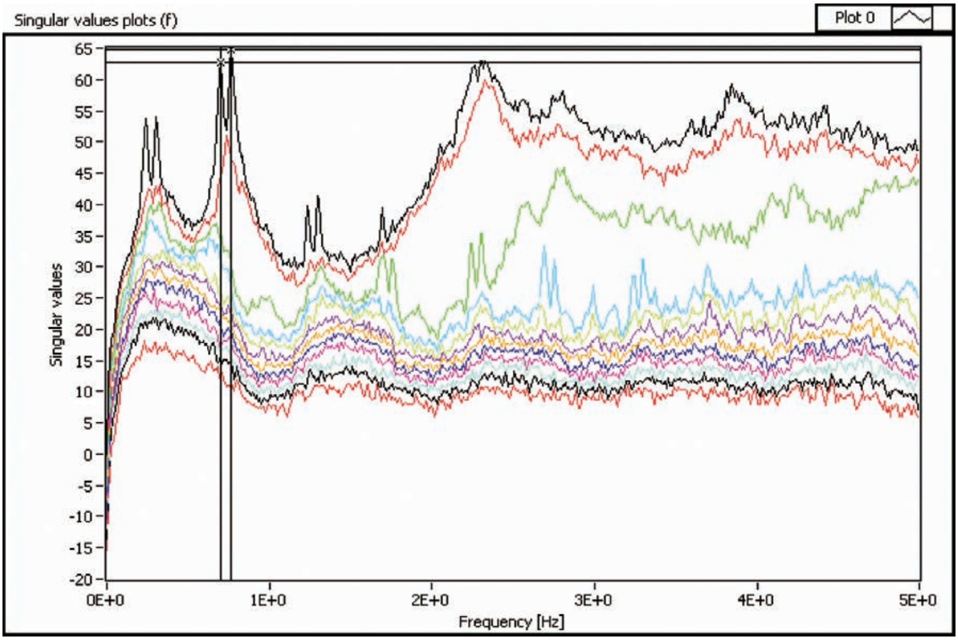

Figure 8. The bell tower of Santa Maria del Carmine – singular value plots.

6. Conclusions

Dynamic tests, together with model updating techniques, represent an alternative approach to structural assessments, especially for historical structures that cannot be destructively tested due to their valuable characteristics. The results of periodic modal tests can be used for damage assessment following events such as seismic events.

In this article, two case studies were discussed. In addition, test layouts and results were discussed, and the positive performance of operational modal analysis techniques for identifying the dynamic properties of structures in the presence of low levels of vibration was demonstrated. An overview of the applications of modal identification results was also given to show the potentialities of output-only modal analysis techniques for structural and health assessments of heritage structures.

Acknowledgements – This research was conducted within the framework of the research activities of the INTERREG MEETING Research Project "Mitigation of Earthquake Effects in Towns and Industrial Regional Districts", and support from this project is gratefully acknowledged. The scientific coordinators Prof. L. Deseri and Prof. G. Fabbrocino are also thanked.

The authors would like to thank Dr. Ceroni and Strago (www.strago.it) for the opportunity to test the OMA software using third party measurements.

References

Andersen, P. (1997): Identification of civil engineering structures using vector ARMA models, PhD Thesis, Department of Building Technology and Structural Engineering, Aalborg University, Aalborg, Denmark, 244 pp, ISSN 1395-7953 R9724.

Bendat, J. S. and Piersol, A. G. (1986): *Random data: Analysis and measurement procedures*. John Wiley and Sons, New York, USA, 566 pp.

Bendat, J. S. and Piersol, A. G. (1993): *Engineering applications of correlation and spectral analysis*. John Wiley and Sons, New York, USA, 458 pp.

Brincker, R., Zhang, L. and Andersen, P. (2000): Modal identification from ambient responses using frequency domain decomposition, in *Proceedings of the 18th International Modal Analysis Conference*, San Antonio, TX, USA, 625–630.

Ceroni, F., Pecce, M. and Voto, S. (2007a): Historical, architectonic and structural investigations of the Bell Tower of Santa Maria del Carmine, *J. Build. Apprais.*, **3**, 155–179.

Ceroni, F., Pecce M., Manfredi G. and Palmaccio F. (2007b): Analisi sismica del Campanile del Carmine in Napoli, in *Proceedings of the XII ANIDIS Conference "L'Ingegneria Sismica in Italia"*, Pisa, Italy, paper 292, 12. (in Italian)

Consiglio Superiore dei Lavori Pubblici (2008): Nuove Norme Tecniche per le Costruzioni, D. M. Infrastrutture 14/01/2008, Published on S.O. n. 30 at the G.U. 04/02/2008 n. 29, 428 pp. (in Italian)

DPCM-NTC2008 (2010): Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale allineate alle nuove Norme tecniche per le costruzioni (d.m. 14 gennaio 2008), Circolare 26/2010, Ministero dei Beni e le Attività Culturali, 431 pp. (in Italian)

Doebling, S. W., Farrar, C. R., Prime, M. B. and Shevitz, D. W. (1996): Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review, *Technical Report LA-13070-MS*, UC-900, Los Alamos National Laboratory, New Mexico, USA, 127 pp.

Fassois, D. (2001): MIMO LMS-ARMAX identification of vibrating structures – Part I: The method, *Mech. Syst. Signal Pr.*, **15**, 723–735.

Gade, S., Møller, N. B., Herlufsen, H. and Konstantin-Hansen, H. (2005): Frequency domain techniques for operational modal analysis, in *Proceedings of the 1st International Operational Modal Analysis Conference*, edited by R. Brincker and N. Møller, Copenhagen, Denmark, 261–271.

Gentile, C. (2005): Operational modal analysis and assessment of historical structures, in *Proceedings of the 1st International Operational Modal Analysis Conference*, Copenhagen, Denmark, 213–224, http://www.iomac.org/pages/2005/CDPre/

Hermans, L., Van Der Auweraer, H. and Guillaume, P. (1998): A frequency domain maximum likelihood approach for the extraction of modal parameters from output-only data, in *Proceedings of the 23rd ISMA Conference on Noise and Vibration Engineering*, Leuven, Belgium, 367–376.

Heylen, W., Lammens, S. and Sas, P. (2007): *Modal analysis theory and testing*. Katholieke Universiteit Leuven, Leuven, Belgium, 306 pp, ISBN 90-73802-61-X.

Jùlio, E. N. B. S., Rebelo, C. A. d. S. and Gouveia D. A. S. (2008): Structural assessment of the tower of the University of Coimbra by modal identification, *Eng. Struct.*, **30**, 3468–3477.

Rainieri, C., Fabbrocino, G., Cosenza, E. and Manfredi, G. (2007): Implementation of OMA procedures using LabView, in *Proceedings of the 2nd International Operational Modal Analysis Conference*, Copenhagen, Denmark, 1–12, http://www.iomac.org/pages/2007/CDPre/

Rainieri, C. and Fabbrocino, G. (2008): Operational modal analysis: overview and applications, in *Strategies for Reduction of the Seismic Risk*, 29–44, ISBN 978-88-88102-15-3.

Rainieri, C. (2008): Operational modal analysis for seismic protection of structures, PhD Thesis, University of Naples “Federico II”, Naples, Italy, 363 pp.

Siola, U. (1990): La Mostra d’Oltremare e Fuorigrotta, Electa Napoli, Naples, Italy, 168 pp. (in Italian)

Van Overschee, P. and De Moor, B. (1994): N4SID: Subspace algorithms for the identification of combined deterministic-stochastic systems, *Automatica*, **30**, 75–93.

Van Overschee, P. and De Moor, B. (1996): *Subspace identification for linear systems: Theory, implementation, applications*. Kluwer Academic Publishers, Dordrecht, the Netherlands, 248 pp.

Zhang, L., Brincker, R. and Andersen, P. (2005): An overview of operational modal analysis: Major development and issues, in *Proceedings of the 1st International Operational Modal Analysis Conference*, edited by R. Brincker and N. Møller, Copenhagen, Denmark, 179–190.

SAŽETAK

Operativna modalna analiza za određivanje svojstava povijesnih građevina

Carlo Rainieri i Giovanni Fabbrocino

Ocjena i smanjenje seizmičkog rizika kod povijesnih građevina, zahtijevaju odgovarajuće poznavanje značajki ponašanja takvih konstrukcija, kako to sugeriraju nedavno objavljene nacionalne i međunarodne smjernice za građevine koje spadaju u kulturnu baštinu. Doduše, povijesne građevine su velika nepoznanica što se tiče svojstava materijala i konstrukcijskih sustava, a usto su podložne izmjenama, propadanju te promjenama tipa konstrukcije. Bolji uvid se može dobiti s procjenom dinamičkih svojstava modela konstrukcije, a dobiveni rezultati mogu se upotrijebiti za povećanje preciznosti i kvalitete numeričkih modela za realne konstrukcije. Štoviše, povremeno opažanje relevantnih parametara može pomoći identifikaciji možebitnih procesa propadanja. Zbog toga, dinamički pokusi, povezani s proračunskim modelima, postaju pouzdan alat kao nerazorne metode procjena stanja povijesnih građevina. U članku se razmatraju osnovna načela dinamičke identifikacije u uvjetima upotrebe konstrukcije. Opisana su dva pokusa na modelima povijesnih građevina, a prikazani su i najvažniji rezultati. Raspravlja se o velikoj djelotvornosti tehnike operativne modalne analize te o interesantnim mogućnostima koje ta tehnika pruža za procjenu povijesnih građevina.

Ključne riječi: povijesne građevine, pokus ambijentalnih vibracija, operativna modalna analiza

Corresponding author’s address: Carlo Rainieri, Structural and Geotechnical Dynamics Laboratory StreGa, Department of S.A.V.A., University of Molise, Via De Sanctis, 86100 Campobasso, Italy, tel. +39 0874 404 935, fax: +39 0874 404 952, e-mail: carlo.rainieri@unimol.it