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PERFORMANCE ASSESSMENT OF SELECTED OMA TECHNIQUES FOR DYNAMIC IDENTIFICATION OF GEOTECHNICAL SYSTEMS AND CLOSELY SPACED STRUCTURAL MODES

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Output-only modal analysis techniques and dynamic monitoring for vibration-based structural health assessment are primary tools for the investigation of the dynamic behavior even of very complex systems. An increasing attention towards these techniques and the opportunities they offer is rising also in the civil engineering field. In the present paper, the attention is focused on the possibility to enhance the knowledge about specific civil engineering systems using traditional and innovative operational modal analysis (OMA) methods. Two case studies are presented: one is focused on the assessment of the performance of the Second Order Blind Identification for output-only modal analysis in the presence of closely spaced modes. In the other, OMA is applied to the simulated dynamic response of an embedded retaining wall. Encouraging results are obtained, pointing out that OMA can be confidently applied also to the analysis of wall vibrations induced by propagating waves.

Key words: Operational Modal Analysis, Second Order Blind Identification, close modes, retaining wall, geotechnical structures

1. Introduction

The continuous development of high performance materials for civil engineering and the enhancement of numerical methods for static and dynamic analysis of structures have led to an increasing complexity of buildings and infrastructures. In addition, higher stress levels for optimal exploitation of materials and structural solutions can be achieved, on the analogy with the approaches to structural design optimization of mechanical, aerospace and automotive systems.

In a similar context, the technology transfer from mechanical and aerospace towards civil engineering applications has determined also an increasing interest in, and the enhancement of, advanced experimental and analytical techniques, such as those able to analyze the dynamic response of structures and provide the modal parameters to support calibration and validation of numerical models.

Their primary role is pointed out by challenging problems which often arise, for instance, from unexpected response levels due to dynamic user/structure interaction (Strogatz *et al.*, 2005) and require experimental and theoretical insight in the dynamic response of structures.

On the other hand, the evolution of dynamic properties of structures over their service life represents another key aspect in view of ageing and structural deterioration prevention and, above all, maintenance of critical components and systems. Regular identification of modal parameters, in fact, can play a relevant role in the development of effective structural health monitoring systems (Doebling *et al.*, 1996).

These circumstances led civil engineers to start exploiting a number of techniques, developed in the system identification and experimental modal analysis field, allowing the experimental identification of dynamic properties. Due to the dimensions of civil structures and the difficulty of exciting them properly, an increasing interest towards output-only modal identification (also called Operational Modal Analysis, OMA) techniques has risen over the years, with significant developments mainly in the last decade.

OMA is based on measurements of the structural response to ambient excitation in order to extract the modal characteristics. This is the reason why it is called also ambient or natural-excitation or output-only modal analysis. It is very attractive due to a number of advantages with respect to traditional input-output modal analysis (Mohanty, 2005; Cunha and Caetano, 2005):

- it is faster and cheaper than input-output techniques;
- no excitation equipment is needed, neither boundary condition simulation;
- it does not interfere with the normal use of the structure;
- it allows the identification of modal parameters which are representative of the whole system under real service conditions;
- it is more suitable for automation and, therefore, for vibration-based structural health monitoring and damage detection applications (Rainieri and Fabbrocino, 2010).

Even if most OMA techniques are derived from traditional input-output modal analysis procedures, the main difference is related to the basic assumptions about the input. OMA methods are based on random responses rather than a deterministic input; thus they rely on a stochastic approach and can be seen as the stochastic counterpart of the deterministic methods used in the classical experimental modal analysis.

OMA is based on the assumption that the input is a Gaussian white noise, characterized by a flat spectrum in the frequency range of interest. As a consequence, modes are uniformly excited and extracted by appropriate procedures. Other assumptions are:

- linearity: the response of the system to a certain combination of inputs is equal to the same combination of the corresponding outputs;
- stationarity: the dynamic characteristics of the structure do not change over time, so that the coefficients of the differential equations are constant with respect to time;
- observability: test setup must be defined in a way able to measure the dynamic characteristics of interest (for instance, nodal points must be avoided in order to detect a certain mode).

However, practical applications of the methods show a certain tolerance about the compliance of the structural response with the above mentioned theoretical requirements. In other words, a sufficiently smooth input spectrum and weak non-stationarities and non-linearities do not lead OMA methods to fail and/or produce significant losses in accuracy.

Extensive reviews of OMA methods can be found in the literature (Peeters, 2000; Rainieri, 2008; Zhang *et al.*, 2005). They have been successfully applied to a large variety of mechanical systems and structures including cars and airplanes (Peeters *et al.*, 2005), towers and bridges (Gentile, 2005). Innovative applications concern the identification, through field tests based on microtremor measurements, of the site period of a soil deposit (Ventura and Thibert, 2007) and the shear wave velocity and shear stiffness modulus profiles (Carvajal and Ventura, 2009) for seismic design purposes.

OMA is an active research area also from a theoretical point of view, with the development of new procedures or adjustment of algorithms borrowed from different contexts and research fields. Among them, an increasing interest is raising towards the application of Blind Source Separation (BSS) techniques (Ans *et al.*, 1985) to output-only modal analysis. A very promising procedure in this context is represented by the Second Order Blind Identification (SOBI) algorithm (Poncelet *et al.*, 2007). However, limitations in the possibility to identify closely spaced modes are remarked in the literature (McNeill and Zimmerman, 2008).

In the present paper, the application of traditional and innovative OMA techniques to the identification of challenging structural systems is investigated. In particular, the attention is first focused on flexible retaining walls, used to adapt soil profiles and ensure stability of excavated areas. The overall dynamic response of the system is the result of relevant soil-structure interactions and wave propagation phenomena. Thus, the dynamic identification of such a system represents a challenging task. Simulated data provided by FEM analysis are processed to assess the ability of OMA techniques to shed light on the dynamic response of such complex geotechnical systems. As a consequence, the obtained results represent a preliminary validation step for the use of OMA techniques to the vibration-based Structural Health Monitoring even of embedded retaining walls (Fabbrocino *et al.*, 2009).

In the second part of the paper, instead, the opportunities and limitations in the identification of closely spaced modes by SOBI are quantitatively investigated through its application to simulated data obtained from a simple FE model. The results are also further validated through its application to a real case study.

2. The modal parameter identification techniques: basics

Different methods for the output-only modal parameter estimation have been adopted in the present research: the (Covariance Driven) Stochastic Subspace Identification (Cov-SSI) (Peeters, 2000), the Frequency Domain Decomposition (FDD) (Brincker *et al.*, 2000) and the Second Order Blind Identification (SOBI) (Poncelet *et al.*, 2007). The present section briefly reports the basis of the above mentioned reference methods.

The Frequency Domain Decomposition is a frequency domain, non parametric output-only modal identification technique based on the Singular Value Decomposition (SVD) of the output Power Spectral Density (PSD) matrix. Structural resonances are identified from the singular value plots through a peak picking process; the corresponding singular vector is a good estimate of the mode shape. In the enhanced version of FDD, damping is estimated by Inverse Fast Fourier Transform of the Auto Power Spectral Density function of the Single Degree Of Freedom (SDOF) system corresponding to the mode, which is identified around the peak of the singular value plot by comparing the mode shape estimate at the resonance with the singular vectors associated to the frequency lines around the peak and retaining all lines above a preset threshold of vector correlation.

The Stochastic Subspace Identification, conversely, is a time domain, parametric modal identification procedure based on a state-space description of the dynamic problem. The modal parameters are extracted from realizations of the state matrix and output matrix of the system obtained from the measurements of its response to ambient vibrations through projections and other algebraic operators. In Cov-SSI, the extraction of the modal properties is based on the preliminary computation of the covariance matrix of the responses and on the construction of a Toeplitz matrix of the covariances (Peeters, 2000).

When applied to OMA, SOBI can be referred to as a non-parametric time domain method, since no *a priori* model is fitted to the data but it simply takes advantage of their temporal structure to exploit the modal information. It is a BSS technique that, given a series of observed signals, aims at recovering the underlying sources. It is shown that, under given assumptions, the modal coordinates act as virtual sources (Poncelet *et al.*, 2007), thus allowing application of such a methodology for modal parameter identification in output-only conditions. The definition of virtual sources (Kerschen *et al.*, 2007) establishes a one-to-one relationship between the mixing matrix and the mode shapes on one hand, and the sources and the modal coordinates on the other hand. Thus, the mode shapes are obtained from the columns of the mixing matrix, while natural frequencies and damping ratios are obtained through curve fitting of the sources. The method is based on second order statistics; in particular, the Joint Approximate Diagonalization (JAD) of a number of correlation matrices is achieved through a numerical algorithm (Belouchrani *et al.*, 1997). The main limitation of the method lies in the requirement of distinct modal coordinates. Thus, a quantitative evaluation of the effect of the spectral difference on the accuracy of modal identification results is certainly of interest for practical applications.

3. Case study #1: The retaining wall

In the present section, the identification, through OMA techniques, of the fundamental dynamic properties of embedded retaining walls from the vibrations induced by travelling waves is analysed. The study is a part of a wider research activity focused on static and dynamic monitoring of a full scale embedded retaining wall (Fabbrocino *et al.*, 2009) and it represents a validation of the possibility to apply OMA to the analysis of complex geotechnical systems, heavily interacting with soil such as the embedded retaining walls.

A sample FE model of a wall-soil, system has been set; soil properties adopted in the dynamic analyses are briefly reported in Table 1.

Table 1. Soil properties adopted in the FE model

Soil layer	Material type	E_0 [10^5 kPa]	G_0 [10^5 kPa]	ν [–]	γ [kN/m^3]	V_s [m/s]	H_L [m]	H_R [m]
A	LE	3.188	1.113	0.432	18.00	246.2	8	3
B	LE	4.086	1.433	0.426	19.03	271.6	3	3
C	LE	14.51	5.045	0.438	19.47	503.9	5	5
D	LE	26.49	9.243	0.433	19.98	673.3	20	4

H_L [m] – Left of wall; H_R [m] – Right of wall

Due to a very low amplitude of ambient vibrations, linear elastic behaviour of the system in operational conditions can be assumed. As a consequence, a linear elastic model has been set, characterized by a medium mesh refined twice nearby the wall, absorbent boundaries, Rayleigh damping (1% for the fundamental modes) and a B/H ratio equal to 20, B and H being the width and the height of the model, respectively.

A dynamic time-history analysis of the system has been carried out by applying a prescribed displacement at the base of the model (representing the bedrock) as the input. The applied input is a zero mean, unit variance Gaussian white noise, sampled at 100 Hz and 3600 s long. The dynamic response of the system to the applied input has been collected at ten uniformly distributed locations (2 m far off each other) along the wall (modelled as a plate element).

Then, the FDD and Cov-SSI methods have been applied to the simulated measurements of the wall response to carry out an output-only identification of the fundamental dynamic properties of the system. When FDD has been applied to the simulated data, a 66% overlap and a Hanning window have been used in spectrum computation.

The obtained values of the fundamental frequencies and damping ratios of the system are reported in Table 2, while the mode shapes of the wall at the fundamental frequencies are shown in Fig. 1. There are no inversions in the sign of the displacements, but in the second mode shape it is possible to observe a change in the curvature. The MAC (Allemang and Brown, 1982) computed between the shapes provided by two OMA methods (Table 2) and comparisons in terms of estimated fundamental frequencies point out a fairly good agreement. The lower value of the MAC for the second mode can be addressed to numerical problems: in fact, the mode shape vectors provided by Cov-SSI show some slight imaginary components at the positions characterized by the lower displacements (bottom part of the wall) and they affect the correlation with the (real) vectors provided by the FDD.

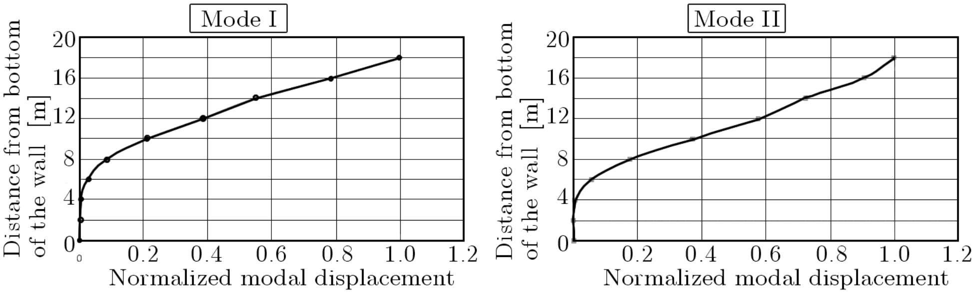

Fig. 1. Mode shapes of the wall at its fundamental frequencies

Table 2. The embedded retaining wall: summary of the results

#	f_{FDD} [Hz]	f_{SSI} [Hz]	Δf [%]	ξ_{SSI} [%]	MAC($\boldsymbol{\psi}_{FDD}, \boldsymbol{\psi}_{SSI}$)
I	3.65	3.65	–	1.03	≈ 1
II	7.45	7.45	–	0.97	0.98

The consistency of the cross checks reveals that OMA techniques can be successfully applied to the output-only modal identification of embedded retaining walls.

4. Case study #2: SOBI and closely spaced modes

In this section, the attention is focused on the performance of SOBI for the output-only modal identification of structures characterized by closely spaced modes.

Since the separation of the sources from their mixture by SOBI is based on their temporal structure (the source separation is possible if the sources are stationary and have different autocorrelation functions, apart from their statistical distribution), modes are required to be characterized by a certain spectral difference to be identified and it is not possible to deal with repeated frequencies. The problem of identification of closely spaced or even coincident modes is already reported in the literature (see, for instance: Zhou and Chelidze, 2007; McNeill and Zimmerman, 2008). In particular, it is stated that distinct modal coordinates automatically satisfy the requirement about the spectral difference (Zhou and Chelidze, 2007); moreover, it is possible to achieve separation even in the case of small spectral differences if the mode shapes partitioned to the sensor locations are linearly independent (McNeill and Zimmerman, 2008) and this can always be accomplished by a judicious choice of sensor locations. Apart from this qualitative information, a quantitative assessment of the performance of SOBI for the output-only modal identification of structures characterized by closely spaced modes is still missing.

In order to assess the accuracy and reliability of results and the quality of separation in the case of close modes, a simple FE model has been set, and its stiffness changed in order to control the spacing of the first two modes quantified by the modal overlap factor (Srikantha Phani and Woodhouse, 2007)

$$\mu_n = \frac{f_n \zeta_n}{f_n - f_{n-1}} \tag{4.1}$$

where f_n and ζ_n represent natural the frequency and damping ratio of the n-th mode, respectively.

The FE model has been implemented through the SAP2000 v.12 computer code and it is a 1 story, 1 bay 3D reinforced concrete frame with the following characteristics (units: kg and m):

- dimensions of the beam section: 0.30×0.30;
- dimensions of the column section: minor dimension equal to 0.30; major dimension ranging from 0.32 to 0.35; the larger inertia is in the y direction; columns are fully restrained;
- beams and columns provide only stiffness; the mass is applied to the master joint (center of the mass) at the level of the roof; the nodes at the floor level are constrained by a rigid diaphragm;
- the values of masses in the master joint along x, y are $m_x = 40000$, $m_y = 44000$, respectively, while the rotational mass is $m_{Rz} = 40000$;
- constant damping ratio equal to 0.01;
- Gaussian white noise (3600 s long, sampled at 100 Hz, zero mean, unit variance) is applied as the input ground motion in both the x and y directions and a linear modal time history analysis is carried out;
- responses in the x and y direction are collected at the four corners of the floor; no noise is added to the simulated measurements; each data set is decimated before processing, obtaining the final sampling frequency equal to 4 Hz.

A picture of the FE model is shown in Fig. 2. The modal overlap factor between the first two modes, which are close, pure translational modes, ranges from 17% to 65% (very close modes); also the case of nearly repeated frequencies is investigated.

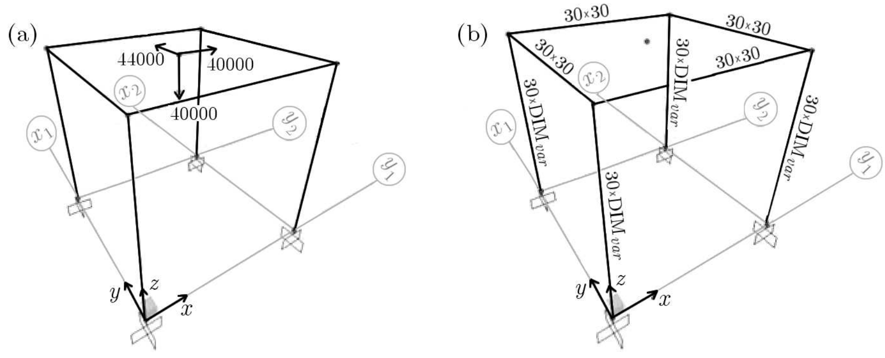

Fig. 2. FE model for the performance assessment of SOBI in the case of closely spaced modes: mass assignment (a), sections (b)

The output-only modal identification by SOBI has been carried out by adopting $p = 500$ and $t = 1 \cdot 10^{-8}$ as the values of the number of correlation matrices to be jointly diagonalised and the threshold to stop JAD, respectively (Cardoso and Souloumiac, 1996).

The assessment of SOBI performance for the output-only modal identification of closely spaced modes has been carried out by comparing the its results with the natural frequencies and mode shapes obtained from the numerical model. In particular, the scatter between the natural frequencies of the FE model and the estimated values by SOBI is computed; the correlation between the mode shapes of the numerical model and the estimates provided by SOBI is evaluated through the MAC index (Allemang and Brown, 1982) as

$$\mathrm{MAC}(\boldsymbol{\psi}^n_{SOBI}, \boldsymbol{\psi}^n_{FEM}) = \frac{|\{\boldsymbol{\psi}^n_{SOBI}\}^\top \boldsymbol{\psi}^n_{FEM}|^2}{(\{\boldsymbol{\psi}^n_{SOBI}\}^\top \boldsymbol{\psi}^n_{SOBI})(\{\boldsymbol{\psi}^n_{FEM}\}^\top \boldsymbol{\psi}^n_{FEM})} \tag{4.2}$$

where $\boldsymbol{\psi}^n_{FEM}$ and $\boldsymbol{\psi}^n_{SOBI}$ are the mode shapes of the n-th mode provided by the FE model and SOBI, respectively. A high correlation is pointed out by values close to 1; conversely, the closer the MAC value to 0, the poorer the correlation. The results are summarized in Table 3. They point out that fairly good modal identification results can be obtained even in the case of closely spaced modes. The sources are properly separated (Fig. 3) and the natural frequencies are accurately identified. Also the mode shape estimates are generally fairly accurate, if a minimum spectral difference is ensured. In

Table 3. Closely spaced modes: SOBI performance assessment for OMA

Larger section dimen. [m]	Modal overlap factor [%]	$f_{1,F}$ [Hz]	$f_{2,F}$ [Hz]	$f_{1,S}$ [Hz]	$f_{2,S}$ [Hz]	$\mathrm{M}_{1,1}$	$\mathrm{M}_{2,2}$	$\mathrm{M}_{1,2}$	$\xi_{1,S}$ [%]	$\xi_{2,S}$ [%]
0.350	17	1.32	1.40	1.32	1.40	0.98	0.99	0.05	1.16	1.07
0.340	27	1.31	1.36	1.30	1.35	0.99	≈ 1.0	0.01	0.96	0.97
0.330	44	1.29	1.32	1.30	1.32	0.99	0.95	0.09	0.92	1.16
0.325	65	1.28	1.30	1.29	1.30	≈ 1.0	≈ 1.0	≈ 0	1.04	0.86
0.320	NRF	1.27	1.28	1.27	1.28	0.58	0.55	0.98	0.71	0.82

$f_{i,F} = f_{i,FEM}$, $f_{i,S} = f_{i,SOBI}$, $\xi_{i,S} = \xi_{i,SOBI}$, $i = 1,2$
$\mathrm{M}_{1,1} = \mathrm{MAC}(\psi_{1,FEM}, \psi_{1,SOBI})$, $\mathrm{M}_{2,2} = \mathrm{MAC}(\psi_{2,FEM}, \psi_{2,SOBI})$,
$\mathrm{M}_{1,2} = \mathrm{MAC}(\psi_{1,SOBI}, \psi_{2,SOBI}$
NRF – nearly repeated frequencies

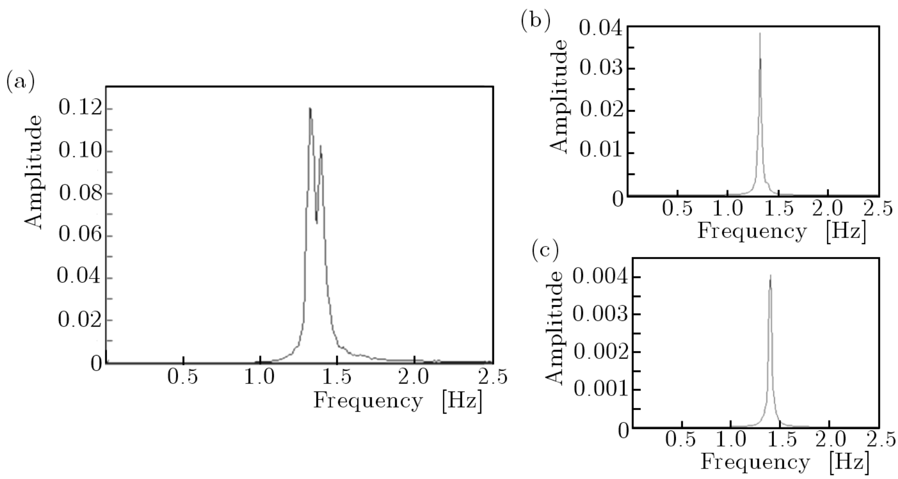

Fig. 3. 17% modal overlap: cross-spectrum between two orthogonal measurement directions (a) and extracted sources corresponding to the first (b) and second (c) mode

the case of nearly repeated frequencies, instead, even if two distinct sources are apparently extracted (Fig. 4), the mode shapes are not accurately estimated. The comparison of the mode shape estimates associated to these two sources points out that the obtained vectors are very similar $\mathrm{MAC}(\boldsymbol{\psi}^1_{SOBI}, \boldsymbol{\psi}^2_{SOBI}) = 0.98$. This proves, as expected, that SOBI is unable to carry out a proper separation of the modes in the case of repeated frequencies, since the mode shape vectors, as provided by the FE model, should theoretically be orthogonal (MAC ≈ 0). This limitation is reflected also by the poor correlation between the mode shapes provided by SOBI and the FE model (MAC ≈ 0.6).

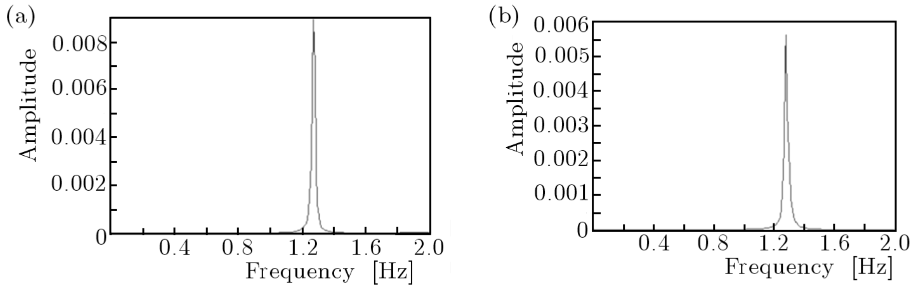

Fig. 4. Nearly repeated frequencies: spectra of the sources at 1.27 Hz (a) and 1.28 Hz (b)

SOBI performance in the case of closely spaced modes has been tested also against a real data set: the RC0 record of the School of Engineering Main Building in Naples (Rainieri *et al.*, 2010). In this case, the first two modes are characterized by a moderate overlap factor (17%). The related Singular Value plots provided by FDD is shown in Fig. 5. The obtained results are reported in Table 4 in comparison with those provided by FDD and Cov-SSI, pointing out that fairly good results can be obtained also in the case of real measurements which take into account the effect of measurement noise. However, a detailed investigation about the effect of noise on the performance of SOBI for the output-only modal identification of structures characterized by close modes is out of the scope of the present paper.

Table 4. The School of Engineering Main Building (Naples): RC0 record – comparison of output-only modal identification results

Mode	SOBI		EFDD		Cov-SSI	
	Natural frequency [Hz]	Damping ratio [%]	Natural frequency [Hz]	Damping ratio [%]	Natural frequency [Hz]	Damping ratio [%]
I	0.92	0.85	0.92	1.03	0.92	1.07
II	0.98	0.92	0.98	1.25	0.98	1.08
III	1.30	0.76	1.30	1.03	1.30	0.82

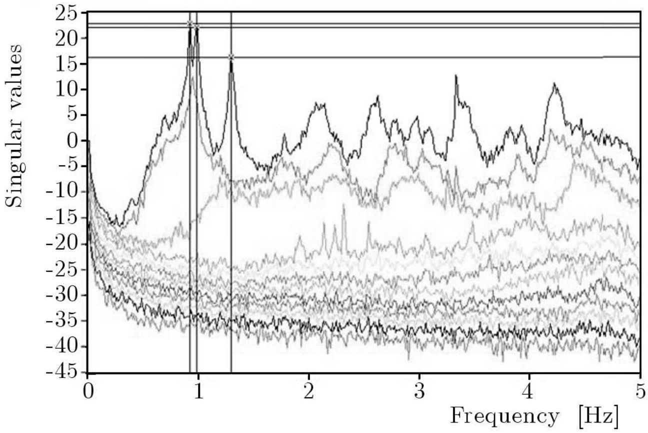

Fig. 5. The School of Engineering Main Building (Naples): RC0 record – Singular Value plot

5. Conclusions

Opportunities offered by traditional and innovative OMA procedures for the analysis of complex structural and geotechnical systems have been discussed. In particular, the applicability of OMA to the identification of the fundamental dynamic properties of embedded retaining walls has been investigated. Moreover, in the case of systems characterized by closely spaced modes, the performance of an emerging technique for OMA, the Second Order Blind Identification, has been quantitatively assessed through its application to simulated and real measurements. The obtained results point out that OMA can be successfully applied also to the characterization of the dynamic behavior of complex geotechnical systems, such as embedded retaining walls in operational conditions. On the other hand, SOBI can be reliably applied even in the case of structures characterized by very closely spaced modes (65% modal overlap), provided that there are no repeated frequencies.

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References

1. Allemang R.J., Brown D.L., 1982, A correlation coefficient for modal vector analysis, *Proc. The 1st SEM International Modal Analysis Conference*, Orlando, FL, USA

2. Ans B., Hérault J., Jutten C., 1985, Adaptive neural architectures: detection of primitives, *COGNITIVA'85*, 593-597

3. Belouchrani A., Abed-Meraim K., Cardoso J.F., Moulines E., 1997, A blind source separation technique using second-order statistics, *IEEE Transactions on Signal Processing*, **45**, 434-444

4. Brincker R., Zhang L., Andersen P., 2000, Modal identification from ambient responses using frequency domain decomposition, *Proc. The 18th SEM International Modal Analysis Conference*, San Antonio, TX, USA

5. Cardoso J.F., Souloumiac A., 1996, Jacobi angles for simultaneous diagonalization, *SIAM Journal of Matrix Analysis and Applications*, **17**, 161-164

6. Carvajal J.C., Ventura C.E., 2009, Identification of operational mode shapes of a soil deposit using a grid of microtremor measurements, *Proc. The 3rd International Operational Modal Analysis Conference*, Portonovo, Italy

7. Cunha A., Caetano E., 2005, From input-output to output-only modal identification of civil engineering structures, *Proc. The 1st International Operational Modal Analysis Conference*, Copenhagen, Denmark

8. Doebling S.W., Farrar C.R., Prime M.B., 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 87545, USA

9. Fabbrocino G., Laorenza C., Rainieri C., Santucci De Magistris F., 2009, Seismic monitoring of structural and geotechnical integrated systems, *Materials Forum*, **33**, 404-419

10. Gentile C., 2005, Operational modal analysis and assessment of historical structures, *Proc. The 1st International Operational Modal Analysis Conference*, Copenhagen, Denmark

11. Kerschen G., Poncelet F., Golinval J.C., 2007, Physical interpretation of independent component analysis in structural dynamics, *Mechanical Systems and Signal Processing*, **21**, 1561-1575

12. McNeill S.I., Zimmerman D.C., 2008, A framework for blind modal identification using joint approximate diagonalization, *Mechanical Systems and Signal Processing*, **22**, 1526-1548

13. Mohanty P., 2005, Operational Modal Analysis in the presence of harmonic excitations, Ph.D. Thesis, Technische Universiteit Delft, The Netherlands
14. Peeters B., 2000, System identification and damage detection in civil engineering, Ph.D. Thesis, Katholieke Universiteit Leuven, Leuven, Belgium
15. Peeters B., Van der Auweraer H., Pauwels S., Debille J., 2005, An Overview of Operational Modal Analysis: Major Development and Issues, *Proc. The 1st International Operational Modal Analysis Conference*, Copenhagen, Denmark
16. Poncelet F., Kerschen G., Golinval J.C., Verhelst D., 2007, Output-only modal analysis using blind source separation techniques, *Mechanical Systems and Signal Processing*, **21**, 2335-2358
17. Rainieri C., 2008, Operational Modal Analysis for seismic protection of structures, Ph.D. Thesis, University of Naples "Federico II", Naples, Italy
18. Rainieri C., Fabbrocino G., 2010, Automated output-only dynamic identification of civil engineering structures, *Mechanical Systems and Signal Processing*, **24**, 678-695
19. Rainieri C., Fabbrocino G., Cosenza E., 2010, Integrated seismic early warning and structural health monitoring of critical civil infrastructures in seismically prone areas, *Structural Health Monitoring – An International Journal*, doi:10.1177/1475921710373296
20. Srikantha Phani A., Woodhouse J., 2007, Viscous damping identification in linear vibration, *Journal of Sound and Vibration*, **303**, 475-500
21. Strogatz S.H., Abrams D.M., McRobie A., Eckhardt B., Ott E., 2005, Theoretical mechanics: crowd synchrony on the Millennium Bridge, *Nature*, **438** (7064)
22. Ventura C.E., Thibert K., 2007, Analysis of microtremor measurements by the frequency domain decomposition method, *Proc. The 2nd International Operational Modal Analysis Conference*, Copenhagen, Denmark
23. Zhang L., Brincker R., Andersen P., 2005, An Overview of Operational Modal Analysis: Major Development and Issues, *Proc. The 1st International Operational Modal Analysis Conference*, Copenhagen, Denmark
24. Zhou W., Chelidze D., 2007, Blind source separation based vibration mode identification, *Mechanical Systems and Signal Processing*, **21**, 3072-3087

Ocena sprawności wybranych typów operacyjnej analizy modalnej do identyfikacji bliskich postaci drgań w konstrukcjach geotechnicznych

Streszczenie

Analiza modalna typu „output-only" i dynamiczne monitorowanie stanu konstrukcji na podstawie obserwacji drgań stanowią podstawowe narzędzia do badania

dynamiki nawet bardzo złożonych układów. Wzrastające zainteresowanie takimi technikami i możliwościami, jakie oferują, odnotowuje się również w dziedzinie inżynierii lądowej. W prezentowanej pracy uwagę skupiono na możliwości pozyskiwania lepszej informacji o specyficznych układach konstrukcyjnych, poprzez zastosowanie tradycyjnych oraz innowacyjnych metod operacyjnej analizy modalnej (OMA). Przedstawiono dwa przypadki. W pierwszym skoncentrowano się na ocenie efektywności ślepej identyfikacji drugiego rzędu dla przypadku analizy modalnej typu „output-only" układu z bliskimi postaciami drgań własnych. W drugim technikę OMA zastosowano do zasymulowanej dopowiedzi dynamicznej ściany oporowej. Otrzymano zachęcające rezultaty, które wskazały analizę OMA jako godną zaufania przy badaniu drgań ściany wywołanych propagacją fal.

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