Engineering Structures 34 (2012) 436–446

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Robust output-only modal identification and monitoring of buildings in the presence of dynamic interactions for rapid post-earthquake emergency management

C. Rainieri [a], G. Fabbrocino [a,*], G. Manfredi [b], M. Dolce [c]

[a] University of Molise, Structural and Geotechnical Dynamics Lab, Department SAVA, Via Duca Degli Abruzzi, 86039 Termoli, Italy
[b] University of Naples Federico II, Department of Structural Engineering, Via Claudio 21, 80125 Napoli, Italy
[c] Department of Italian Civil Protection, Seismic Risk Office, Via Vitorchiano 4, 00189 Roma, Italy

ARTICLE INFO

Article history:
Received 14 May 2011
Revised 19 September 2011
Accepted 3 October 2011
Available online 11 November 2011

Keywords:
Operational Modal Analysis
Automated dynamic identification
Structural Health Monitoring
Dynamic interaction

ABSTRACT

A common assumption in the theoretical background of Operational Modal Analysis (OMA) methods concerns the input, which is not measured and consists of a Gaussian white noise characterized by a flat spectrum in the bandwidth of interest. Even if a number of applications have shown that OMA works also when the input spectrum is smooth enough, if this assumption is not fulfilled, the modal identification process may become more complex or even fail due to dominant frequency components of the input appearing in response spectra. Thus, specific techniques and strategies have to be applied to sort out structural dynamic properties from frequencies of the input. It is often possible to identify such non-structural frequencies in the case of spurious harmonics due to rotating equipment, but they can be erroneously identified as structural or even bias the estimates, for instance when such harmonics are close to structural modes. About civil structures, spurious frequencies can be due to rotating machines but also to interaction with adjacent constructions. In the present paper, attention is mainly focused on the issue of modes from surrounding structures appearing in the response of the structure under investigation. Thus, natural frequencies of a sample structure are mixed together with those due to interaction with similar surrounding structures, and its response spectra are characterized by several close peaks in a narrow bandwidth. In order to discriminate modal from spurious frequencies, an integrated use of output-only techniques is illustrated and applied to a real test case. An approach aiming at robust evaluation and monitoring of dynamic properties for fast post-earthquake emergency support is proposed and the experimental field validation is discussed in detail.

1. Introduction

A common assumption in the theoretical background of Operational Modal Analysis (OMA) concerns the input, which is not measured and consists of a Gaussian white noise with a flat spectrum in the frequency range of interest. As a consequence, all modes are assumed to be equally excited in this range and they can be extracted by appropriate methods. A number of applications have shown that OMA works also when the input spectrum is smooth enough. However, if this assumption is not fulfilled, the modal parameter identification process may become more complex or even fail due to dominant frequency components appearing in response spectra [1]. It is often possible to identify such non-structural frequencies, but they can sometimes be erroneously identified as structural or even bias the estimates [2].

Civil engineering structures are usually excited by broadband input due to wind, traffic or seismic micro-tremors. However, the input can sometimes show dominant frequency components, which appear also in the output. Such frequency components belonging to the forcing system have to be distinguished from the actual structural resonances.

Spurious dominant frequency components are often associated to the presence of rotating equipment. The problem of combination of a stochastic broadband input with harmonic components, deterministic in nature, is more relevant in the case of mechanical structures, such as in-flight helicopters, running engines [3] and ships in operation [4]. Nevertheless, also civil engineering structures can show harmonic components superimposed to the stochastic response. They can be due, for example, to turbines, generators, ventilation equipment and other mechanical components and systems installed in the buildings or in adjacent areas. In the case of civil engineering structures, however, additional dominant frequency components may appear in the response spectrum as a consequence of dynamic interactions with surrounding structures. In

* Corresponding author. Tel./fax: +39 0874 404 952.
E-mail addresses: carlo.rainieri@unimol.it (C. Rainieri), giovanni.fabbrocino@unimol.it (G. Fabbrocino), gamanfre@unina.it (G. Manfredi), mauro.dolce@protezionecivile.it (M. Dolce).

0141-0296/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2011.10.001

the present paper attention is mainly focused on this second aspect that is less investigated and adequately documented.

Different approaches to solve the problem of discriminating harmonic components due to rotating equipment from actual structural modes in OMA are available in technical literature. This issue is extensively analyzed in [5], where popular OMA methods are reviewed (Polyreference Least Square Complex Exponential [6], Ibrahim Time Domain [7] and Eigensystem Realization Algorithm [8]) and modified in order to manage effects of harmonic excitations. Influence of harmonic components on OMA carried out according to the (Enhanced) Frequency Domain Decomposition procedure [9,10] and the Stochastic Subspace Identification methods [11,12] is investigated and summarized in [13], where a number of methods able to discriminate harmonic components from structural modes are also reported.

From a general point of view, the main drawbacks concerning the presence of deterministic signals superimposed to the stochastic part can be summarized as follows:

- Potential mistakes in identification of modes, that is to say harmonics can be erroneously identified as structural modes.
- Potential bias in mode estimation, affecting natural frequency, damping and/or mode shape, in particular if the spurious harmonic is very close to the structural mode.
- Need of a high dynamic range to extract weakly excited modes in the presence of such harmonics.

Technical literature offers a number of criteria to identify harmonic components in recorded dynamic measurements. In [14] it is observed that harmonics in response spectra can be identified as narrowband resonances whose bandwidth depends on frequency resolution. Thus, the resonance is likely a spurious harmonic if the bandwidth changes with frequency resolution. Alternative strategies rely upon: (1) examination of Short Time Fourier Transform of response signals, (2) rank estimation of the output Power Spectral Density matrix at the frequency of interest via Singular Value Decomposition, (3) rejection of frequencies associated to unlikely modal properties (unrealistic mode shapes, too much low damping ratios) [4,13,15]. Advanced strategies to identify and remove spurious harmonics are based on checks of Probability Density Functions and, in particular, of kurtosis [16,17].

The issue of identification through OMA of structural modes in the presence of spurious dominating frequencies due to dynamic interaction with adjacent structures, on the contrary, is less investigated. The problem has been already analyzed in the literature [18], where it is shown that a careful examination of the peaks in the spectra is required. Spurious peaks are usually identified according to basic criteria in experimental modal analysis. An integrated approach, however, has not been proposed yet.

The herein described research is based on the results of an extended experimental campaign carried out under the coordination of the Italian Civil Protection (DPC) and the Reluis Consortium (www.reluis.it) in the area of the Guardia di Finanza Non-Commissioned Officers' School in Coppito (L'Aquila, Italy). It shows how an integrated use of output-only modal analysis techniques can rationally support identification of spurious frequencies due to interaction with adjacent buildings. Moreover, because of the peculiar framework the experimental campaign has been conducted in, attention is focused also on the possibility, even in the presence of interaction effects, to monitor dynamic properties of buildings in a reliable, effective and automated way for post-earthquake emergency support.

In fact, a systematic dynamic characterization of the buildings in the area of Guardia di Finanza Non-Commissioned Officers' School and installation of effective monitoring systems on some of them are two of the main activities carried out by the group of the Structural and Geotechnical Dynamics Laboratory StreGa under the coordination of the Italian Civil Protection for post-mainshock emergency management and in view of building rehabilitation to host the L'Aquila 2009 G8 meeting. The description of such a complex activity is out of the scope of the present paper, but the relevant number of performed dynamic tests under environmental excitation provided interesting sample cases.

Among them, measurements on four buildings belonging to B1 Block of the Guardia di Finanza School are analyzed. Actually, the test case relevance cannot be addressed to as much narrowband excitation due to rotating parts (even if they have been also identified in response signals) as to interaction effects with other close structures characterized by similar natural frequencies. As a consequence, response spectra show several peaks in a narrow frequency range and only a few of them are related to structural modes; the others are, conversely, correlated to interaction effects among the adjacent structures.

In the following sections, after a short description of the buildings and test layout, the problem of modal identification in the presence of dynamic interaction effects is analyzed. Results obtained from application of different OMA methods are discussed, pointing out how an integrated use of output-only techniques can lead to an effective discrimination of modal from spurious frequencies. Analysis of results provided by automated modal analysis procedures developed in the framework of research activities carried out at the Structural and Geotechnical Dynamics Laboratory StreGa will show that they can be used to build an effective structural monitoring system even in such complex test conditions. Effectiveness and limitations of such a system are discussed in light of real monitoring results.

2. Description of the construction and test layout

2.1. B1 Block overview

B1 of buildings Block is located in the area of the Guardia di Finanza Non-Commissioned Officers' School in Coppito (L'Aquila). It consists of nine similar reinforced concrete moment frame buildings distributed on three lines and covers a rectangular area of 165 m by 66 m.

At time of testing, they were used as residence for cadets. Connection among the different buildings and vertical distribution are ensured by a number of separated reinforced concrete stairs. Indoor stairs are located in the intermediate courtyards; outdoor stairs are located at each building alignment head. Each building and stair structure appeared to be independent of the adjacent ones, since seismic joints were provided in the superstructure. Attention is herein focused on buildings, whose rectangular shape marks the regularity of the reinforced concrete (r.c.) framed structure. Fig. 1 reports some views of the block of interest.

Regularity in elevation from a dynamic standpoint is actually affected by a different arrangement of partitioning walls at the ground level with respect to the upper levels. Notwithstanding an exterior simple structural configuration, very similar among the different buildings constituting the block, some differences in their dynamics could be expected. Since dynamic tests were carried out a few days after the L'Aquila earthquake mainshock on April 6th, 2009, the dynamic response of the buildings was also influenced by the different levels of non-structural damage that affected each single structure.

Identification of their modal properties has been made even more difficult by the fact that different buildings were characterized by quite similar natural frequencies for the first fundamental modes and, as it will be shown in Section 4, such frequencies were located in a narrow frequency range between 2 and 4 Hz. This