Mechanical Systems and Signal Processing 60-61 (2015) 512–534

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Development and validation of an automated operational modal analysis algorithm for vibration-based monitoring and tensile load estimation

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A R T I C L E I N F O

Article history:
Received 3 October 2014
Received in revised form
25 November 2014
Accepted 22 January 2015
Available online 11 February 2015

Keywords:
Ambient vibrations
Automated operational modal analysis
Tensile load estimation
Vibration-based monitoring
Joint approximate diagonalization

A B S T R A C T

In the last few decades large research efforts have been devoted to the development of methods for automated detection of damage and degradation phenomena at an early stage. Modal-based damage detection techniques are well-established methods, whose effectiveness for Level 1 (existence) and Level 2 (location) damage detection is demonstrated by several studies. The indirect estimation of tensile loads in cables and tie-rods is another attractive application of vibration measurements. It provides interesting opportunities for cheap and fast quality checks in the construction phase, as well as for safety evaluations and structural maintenance over the structure lifespan. However, the lack of automated modal identification and tracking procedures has been for long a relevant drawback to the extensive application of the above-mentioned techniques in the engineering practice. An increasing number of field applications of modal-based structural health and performance assessment are appearing after the development of several automated output-only modal identification procedures in the last few years. Nevertheless, additional efforts are still needed to enhance the robustness of automated modal identification algorithms, control the computational efforts and improve the reliability of modal parameter estimates (in particular, damping).

This paper deals with an original algorithm for automated output-only modal parameter estimation. Particular emphasis is given to the extensive validation of the algorithm based on simulated and real datasets in view of continuous monitoring applications. The results point out that the algorithm is fairly robust and demonstrate its ability to provide accurate and precise estimates of the modal parameters, including damping ratios. As a result, it has been used to develop systems for vibration-based estimation of tensile loads in cables and tie-rods. Promising results have been achieved for non-destructive testing as well as continuous monitoring purposes. They are documented in the last sections of the paper.

1. Introduction

Vibration-based Structural Health Monitoring (SHM) is widely recognized as an attractive strategy for early damage detection in civil structures and it is currently going to make the transition from the research domain to the engineering practice [1]. In fact, the recent technological advances have fostered the development of permanent dynamic monitoring

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http://dx.doi.org/10.1016/j.ymssp.2015.01.019

systems by reducing installation and operating costs. Thus, several applications to strategic infrastructures and historical structures are appearing in the literature (see, for instance, [2,3]). From a general point of view, vibration-based SHM systems are used for either long-term monitoring, to check the ability of the structure to perform as designed even in the presence of ageing and natural degradation phenomena, or rapid condition assessment after hazardous (both natural and man-made) events. In order to exploit the advantages of the latest technological developments in the field, the collected data have to be continuously and automatically processed to extract damage sensitive features.

The experimental estimates of the modal properties and some derived quantities (for instance, the mode shape curvature [1]) are the features adopted in modal-based damage detection. Anomalies are identified from the analysis of the variations of the selected features over time, eventually after removal of the effects of environmental and operational factors. Because of the sensitivity of the modal properties to the environmental factors, continuous monitoring is a fundamental requirement to fully exploit the potential of modal-based damage detection techniques. Hence, large research efforts have been devoted to the development of automated output-only modal identification procedures in the last years.

The first systematic analyses and classifications of automated Operational Modal Analysis (OMA) procedures are very recent [4,5]. A firm distinction between "automated modal parameter identification" (MPI) methods and "automated modal tracking" (MT) methods has been proposed. While automated MPI methods estimate the modal parameters from a single dataset without any prior information about the dynamic properties of the structure under investigation [4], MT methods monitor (track) the evolution of the modal parameters of a structure over time taking advantage of a set of reference estimates. For instance, the MT procedure described in [5] requires reference estimates of the mode shapes of the monitored modes. Each mode shape is used to carry out a spatial filtering of data and identify the modal properties of the corresponding mode. The set of reference modal properties can come from either automated or manual modal identification. In spite of their minor autonomy with respect to the automated MPI methods, MT procedures are advantageous for applications requiring short response time and low computational efforts. On the other hand, automated MPI methods are the only option when reference modal parameters are not available or a new reference set has to be automatically estimated.

Another attractive application of automated OMA procedures concerns the indirect estimation of tensile loads in cables and tie-rods from vibration measurements. The inverse problem associated to the evaluation of the tensile axial force from vibration measurements has been investigated in several studies [6–10] because of its promising applicative perspectives in the context of non-destructive testing and SHM. It provides interesting opportunities for cheap and fast quality checks in the construction phase, as well as safety evaluations and structural maintenance over the structure lifespan [11]. An extensive literature review reveals that several vibration-based tensile load estimation methods take advantage of the known input applied by an impact hammer [6–8] and eventually of the results of a numerical model [9]. The application of a known input is usually more relevant in the case of tie-rods. In fact, when OMA is applied, it requires a trade-off between the needs of resolving low amplitude vibrations and, at the same time, of minimizing the dimensions of the sensors so that they do not alter the dynamic response of the member. Nevertheless, the increasing availability of miniaturized, high performance accelerometers and of automated MPI algorithms is fostering the development of ambient vibration-based systems for tensile load estimation and monitoring [12].

The effectiveness of damage detection and tensile load estimation depends on the accuracy of modal parameter estimates, but most of the available automated OMA algorithms suffer common drawbacks [4] that affect their accuracy. They are mainly related to the adoption of statically set thresholds and parameters that have to be tuned at startup [4]. Thus, this work is focused on the development of an automated MPI procedure that tackles the following challenges:

(1) Provide accurate and precise modal parameter estimates, including damping;
(2) not rely on application-dependent parameters that have to be tuned by the user;
(3) be characterized by a high success rate (robustness with respect to problems of false and missed identification); and
(4) allow the control of computational efforts.

The paper first describes the new automated MPI algorithm, pointing out its novelty aspects. Special emphasis is given to the extensive validation of the algorithm based on simulated and real datasets in view of continuous monitoring applications. In particular, validation is pursued by comparing the results of the herein presented procedure with nominal values of the modal properties in the case of simulated data, and with results independently achieved by different automated [4] or manual [13] OMA techniques in the case of real measurements. The validated algorithm is then used to develop systems for vibration-based estimation of tensile loads in cables and tie-rods for non-destructive testing and continuous monitoring purposes. Such systems are herein described in their relevant aspects, and basic results from sample applications are illustrated in order to remark the promising applicative perspectives of the new automated MPI algorithm.

2. Automated modal parameter identification

2.1. Current approaches for the automation of parametric OMA methods

Several automated MPI algorithms have appeared in the literature in recent years. They are based on parametric (see e.g. [14,15]) as well as non-parametric (see e.g. [4,16]) OMA methods. From a general point of view, the automation of parametric MPI methods has followed three main guidelines: development of identification algorithms able to deliver very clear stabilization diagrams