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High spatial resolution modal identification of a stadium suspension roof: Assessment of the estimates uncertainty and of modal contributions

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ABSTRACT

In Operational Modal Analysis (OMA) engineers are usually confronted with the challenge of extracting as much information as possible from the data collected in ambient vibration tests in order to characterize the modal behaviour of the tested structures under environmental and operational conditions. There exist several tools for this purpose that combined can be used to estimate valuable information regarding modal behaviour of the tested structures from the output vibration responses measured in these tests. In this context, this paper describes the strategies and techniques employed, as well as the results obtained from the OMA performed to identify the modal properties of a football stadium suspension roof. The main focus of the paper is the employment of state-of-the-art identification techniques, in time and frequency domain, in order to estimate the modal parameters of the roof structure with high spatial resolution for the mode shapes of vibration together with their uncertainties bounds, as well as to assess the contribution of the identified modes to the measured responses under different environmental and operational conditions. A particular challenge of the presented example is the need to simultaneously process a large number of time series (15 datasets with 12 sensors – 180 time series). At the end of the paper, the estimates provided by the ambient vibration test are compared with the ones obtained with a permanent monitoring system operating during one year, in order to evaluate the representativeness of the results provided by a single ambient vibration test.

1. Introduction

In operational modal analysis (OMA) engineers are usually confronted with the challenge of extracting as much information as possible from the data collected in the Ambient Vibration Tests (AVTs) in order to characterize the modal behaviour of the tested structures under normal operation conditions. In this context, this paper describes the strategies and techniques employed, and the results obtained from the OMA performed to estimate the modal properties of a football stadium suspension roof. Given the particular characteristics of this structure, described in detail in the next section, several studies were carried out to assess the structural behaviour of the suspension roof under varying environmental conditions since the beginning of the structural design [1,2]. The results provided by such studies, as well as those obtained from the numerical simulations and wind tunnel tests performed during the early stage of the structural design have demonstrated that the structure could be susceptible to aero-elastic instabilities.

These conclusions suggested a strict control of the influence of the environmental factors on the structural behaviour which, in turn, led to the installation of static, dynamic and wind monitoring systems during the construction of the structure [3]. These systems were essential during the construction, particularly the static monitoring system which comprised a series of load cells installed in the cable anchorages, embedded instrumentation of the concrete structure (strain gauges, inclinometers and thermometers) and the instrumentation of the rock massifs and foundations with load cells installed in the anchors to the earth and in-place inclinometers.

Shortly after the opening in 2004, a first ambient vibration test (AVT) was performed in 2005 by the Laboratory of Vibrations and Structural Monitoring (ViBest, www.fe.up.pt/vibest) of the Faculty of Engineering of University of Porto (FEUP), to estimate the modal parameters of the roof structure in the frequency range 0–1 Hz and compare the identified modal parameters with the results obtained from numerical simulations developed during the design phase [7].

Afterwards, in 2009, ViBest/FEUP installed two complementary monitoring systems on the suspension roof. One consists of a permanent dynamic system for measurement of the acceleration

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responses [4,5] and the other continuously collects wind and temperature data [6].

In the present study, the processing methodology and the results of a second and more complete AVT carried out in 2011 are presented. The main purpose of this was to estimate the modal parameters of the aforementioned structure with high spatial resolution for the mode shapes of the modes suited in a broader frequency range of 0–2 Hz, very important information to complement the results provided by the monitoring system based in few instrumented points and the initial ambient vibration test based on a coarser spatial resolution that did not allowed an adequate characterization of all the modes that can be tracked by the monitoring system. Aiming at extracting accurate information regarding the dynamic behaviour of the roof structure, state-of-the-art identification techniques such as the poly-reference Least Squares Complex Frequency (pLSCF) [8], the DATA and COVariance-driven Stochastic System Identification (SSI-DATA and SSI-COV) [9], and the poly-reference Maximum Likelihood (ML) Estimator in Modal Model formulation (pMLE-MM) [10] were applied to estimate the modal parameters together with their uncertainties bounds. Apart from the modal identification, the estimation of modal responses was carried to assess the modes which are likely to be more excited by the operational conditions under which the tested structure was subjected during the test. One of the main purposes of the test was to create a baseline reference result to be used by the autonomous monitoring system installed in one of the slabs of the roof in the beginning of 2009 [4]. The test was carried out by measuring the vertical responses induced by environmental sources (e.g., wind and the traffic in the surroundings of the stadium) with two different acquisition systems. The employment of robust pre-processing techniques to synchronize the data collected by both acquisition systems, as well as of the combination of state-of-art parametric OMA techniques, provided an accurate estimation of a large number of modes of the roof structure in the frequency range of 0–2 Hz with high spatial resolution for the corresponding modes shapes of vibration and with confidence intervals for the natural frequencies and modal damping ratios.

The paper is basically divided in four parts. After the characterization of the structure, a theoretical introduction to the applied processing tools and a description of the test, in the first part (Sections 2–4), it is presented the results of a multi-patch OMA performed to estimate the modal parameters of the suspension roof with high spatial resolution for the mode shapes (Sections 5–6). These results were obtained by applying the pLSCF identification and pMLE-MM methods in combination with the Post-Global Estimation Re-scaling (PoGER) strategy [11]. Next, these results were compared to those estimated with Frequency Domain Decomposition (FDD) technique from the vibration data collected in the AVT carried out in 2005 [7]. In the third part of the paper (Section 7), the results of the analysis carried out to assess the variation of the natural frequencies, modal damping ratios and their confidence intervals over the different patches are presented. Finally, in the fourth part of the paper (Section 8), in order assess the representativeness of the estimates provided by the test carried out to estimate the modal parameters of the suspension roof, these estimates are compared to those obtained over the course of one year of monitoring of the roof structure.

2. Description of the structure

The tested structure is located in the city of Braga, Portugal, and corresponds to one of the stadia that were constructed to host some of the matches the European Football Championship that took place in 2004, in Portugal (Fig. 1). The structure is known for its innovative architectural design elaborated by the design office of the Portuguese architect Eduardo Souto Moura, who has won the Pritzker prize of architecture in 2011, in collaboration with the structural design office AFA Consult [3]. The stadium is considered a masterpiece of architecture not only because of its innovative concepts and architectonic characteristics, but also for the perfect integration to the surrounding environment. The

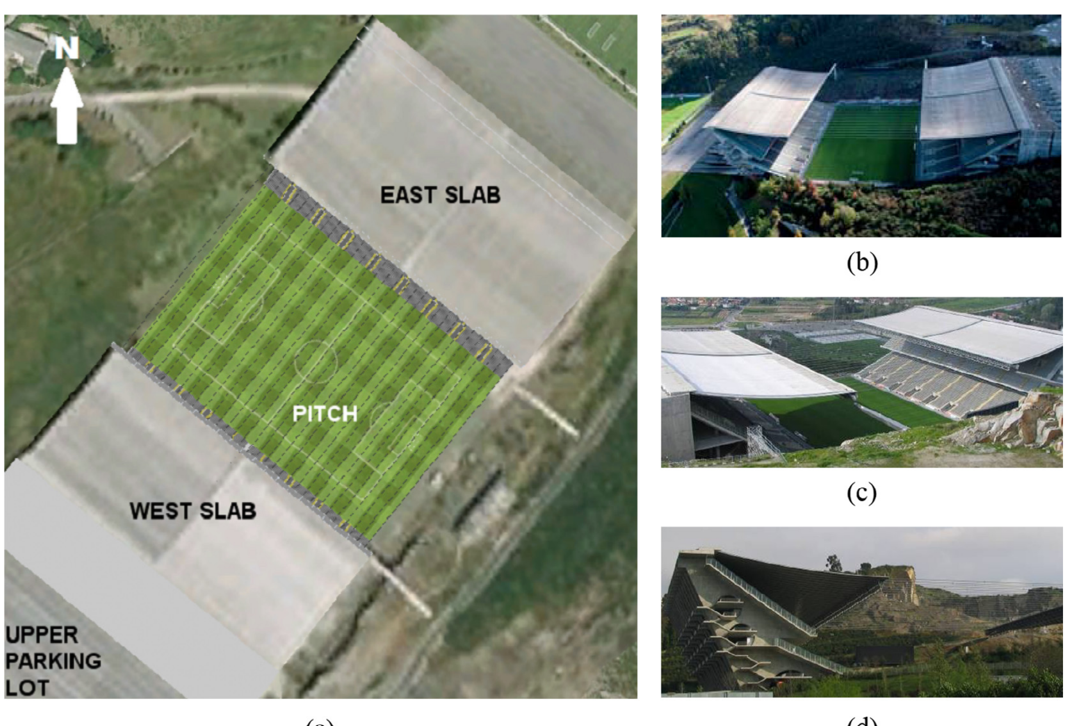

Fig. 1. Braga Municipal Sports Stadium: top view of the stadium (a); lateral view from the east side (b); top view of the roof from the west side (c); and lateral view of the East stand (d).