Engineering Structures 151 (2017) 839–860

Contents lists available at ScienceDirect

Engineering Structures

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

Operational modal analysis of an eleven-span concrete bridge subjected to weak ambient excitations

Ge-Wei Chen [a], Piotr Omenzetter [b,*], Sherif Beskhyroun [c]

[a] School of Civil Engineering, Hunan University of Science and Technology, Xiangtan, China
[b] The LRF Centre for Safety and Reliability Engineering, The University of Aberdeen, Aberdeen, UK
[c] Department of Built Environment Engineering, Auckland University of Technology, Auckland, New Zealand

ARTICLE INFO

Article history:
Received 18 September 2016
Revised 15 June 2017
Accepted 30 August 2017

Keywords:
Ambient vibrations
Bridges
Modal identification
Operational modal analysis
System identification
Weak excitation

ABSTRACT

The challenges of accurately identifying the dynamic characteristics of bridge structures from ambient vibration responses persist because, unlike in the ideal laboratory environment, elevated levels of noise in data are unavoidable at any in-situ testing site and may have detrimental effects on the modal parameter identification process and results. This is especially true for vibration tests conducted under weak ambient excitation sources resulting in poorer signal-to-noise ratios (SNRs). This paper presents an investigation into the feasibility and reliability of modal identification using operational modal analysis (OMA) techniques under such weak excitation circumstances and with responses measured by inexpensive stand-alone accelerometers/data recorders. An eleven-span concrete motorway off-ramp bridge, closed to traffic, was excited only by ground vibrations generated by traffic on the motorway passing underneath the bridge as well as on nearby motorway on- and off-ramps, weak winds, and possible micro tremors. A high spatial resolution of measuring points on the bridge deck was used to collect vibration responses. Three output-only modal parameter identification algorithms were utilised to extract the modal properties, namely the peak picking (PP), the frequency domain decomposition (FDD) and the data driven stochastic subspace identification (SSI) method. Nine lateral and three vertical modal frequencies below 10 Hz could be identified despite the weakness of the environmental excitations and noise in sensors. The identified experimental natural frequencies were stable, damping ratios, however, had a marked scatter. A comparison with the results of a numerical modal analysis using a finite element model revealed, however, that several higher order vertical modes were missing from the experimental results altogether, and some of the OMA methods missed the fundamental lateral mode. Overall the PP method was the most successful in finding the largest number of frequencies but the SSI method yielded the highest quality mode shapes. The SSI method is, however, computationally more expensive that the remaining two methods. For quick, preliminary results, the PP and FDD methods can still be useful and detailed analyses could use SSI and FDD. Overall, the study argues that output-only system identification can provide useful quantitative insights into the modal properties of stiff bridges even under weak environmental excitations, or poorer SNRs, but its limitations need to be acknowledged.

1. Introduction

Experimental modal parameter identification of a structure involves the extraction of modal quantities (i.e. natural frequencies, damping ratios, mode shapes, and, when excitations are measured, also modal masses) from the collected dynamic measurements. The identified modal parameters can be utilised in various analyses including, for instance, model updating [1–3], structural health monitoring [4–6], non-destructive damage assessment [7,8], and vibration mitigation and control [9]. The conventional experimental modal analysis methods, which use the well-established input–output modal identification techniques originally developed for mechanical and aeronautical systems, were first turned to by the civil engineering researchers to accurately identify the main modal properties of large structures such as bridges [10,11] and dams [12,13]. These methods essentially rely on the construction of a set of estimates of either frequency response functions (FRFs) in the frequency domain or the impulse response functions (IRFs) in the time domain by simultaneously measuring the controlled excitation forces and the resulting structural responses. The modal parameters are subsequently

* Corresponding author.
E-mail address: piotr.omenzetter@abdn.ac.uk (P. Omenzetter).

http://dx.doi.org/10.1016/j.engstruct.2017.08.066
0141-0296/

determined by employing optimisation approaches to perform fitting between the measured and theoretical FRFs/IRFs. An extensive overview of such classical input–output modal parameter estimation methods can be found, for example, in the textbooks [14–17]. However, the practitioners of experimental structural dynamics have for some time been increasingly abandoning the very heavy, cumbersome and expensive devices necessary to excite large-size structural systems in a controlled way and have been continuing embracing more and more enthusiastically the more practical operational modal analysis (OMA) approaches, also known as output-only modal techniques [18–19]. These have several compelling characteristics, including most importantly the need to collect only response measurements in operational conditions to derive modal information. Thus, no excitation equipment is needed making OMA inexpensive, convenient and efficient. In OMA, only naturally occurring and/or anthropogenic sources, such as wind, waves, currents, vehicular or pedestrian traffic, operations of machines, activities of occupants, etc., are relied on to excite structures. For data analysis, the input is assumed to be a realisation of a stochastic zero-mean spatially uncorrelated Gaussian white noise process. This theoretical assumption has turned out to be not overly restrictive in practical applications. For example, Peeters and de Roeck [18] demonstrated that if the input spectrum is reasonably flat the output-only methods will produce practically acceptable results.

A range of OMA techniques have been developed to extract the modal parameters of engineering structures by using output-only measurements [18,20]. The methods available are usually classified as belonging to the frequency domain or the time domain. Frequency domain methods start from estimating an output spectrum or half-spectrum matrices from the measured dynamic responses. These methods can be either non-parametric or parametric. The non-parametric frequency domain methods are simpler and were therefore the first to be adopted [21]. They comprise approaches such as the peak picking (PP) method [22,23], the frequency domain decomposition (FDD) method [24], and the enhanced frequency domain decomposition (EFDD) method [25]. Alternatively, parametric identification in the frequency domain is realised by fitting a model, such as the modal model [17], the common-denominator model [26], or the right and left matrix-fraction descriptions [27], to the output spectrum, from which the modal parameters are then extracted. Other frequency domain parametric methods are the PolyMAX [28] and the poly-least squares complex frequency domain (p-LSCF) methods [29]. The time domain methods are essentially parametric, and include the natural excitation technique (NEXT) [30] typically combined with the eigensystem realisation algorithm (ERA) [31,32], the random decrement (RD) technique [33], the Ibrahim time domain (ITD) method [34,35], the auto-regressive moving average vector (ARMAV) technique [36], and the stochastic subspace identification (SSI) techniques [37,38].

A wealth of case studies of the application of OMA to bridge structures can be found in literature and only a small but representative selection can be discussed here. Ren and Zong [39] applied two modal analysis methods, the PP and SSI, to the ambient vibration data from a concrete-filled steel tubular-arch bridge. Magalhães et al. [40] implanted four output-only identification techniques (the PP, FDD, covariance-driven SSI and data-driven SSI) for the modal identification of the International Guadiana cable-stayed bridge. Magalhães et al. [41] processed the acceleration time series recorded during ambient vibration tests of the Millau Viaduct using both the p-LSCF and SSI methods. Siringoringo and Fujino [42] employed two time-domain system identification methods, the RD-ITD and NEXT-ERA, to determine the dynamic characteristics of the Hakucho Suspension Bridge in Japan. He et al. [43] applied three different output-only system identification algorithms, the ERA, EFDD and SSI, to the data collected from ambient and forced vibration tests on a newly built long span suspension bridge in California. Altunişik et al. [44] experimented with both the EFDD and SSI to estimate the dynamic characteristics of the post-tensioned Gülburnu Highway Bridge. Brownjohn et al. [45] applied the NEXT-ERA, SSI and p-LSCF techniques for system identification of the Humber suspension bridge. Gentile and Saisi [46] reported an OMA exercise of the historic Paderno iron arch bridge. The two identification techniques used were the FDD and SSI. Dorvash and Pakzad [47] processed the ambient responses from a steel cantilevered-truss bridge through different time- and frequency-domain algorithms.

However, the investigations described above mainly focused on modal identification and validation applied to signals recorded on relatively long-span, flexible bridges, such as suspension or cable-stayed types. Furthermore, the ambient excitation levels were generally strong, coming from vehicles crossing the bridges or winds acting on flexible decks, and thus the collected vibration responses usually exhibited high signal-to-noise ratios (SNRs). The general conclusion achieved was that it was possible to identify a wide range of modes and the uncertainties in natural frequency results were much smaller than for damping ratios. For cases of bridges with stiff, short to moderate span lengths and subjected only to weak environmental excitation sources, much less OMA research efforts and results have been reported so far. However, the practitioners of the art of experimental dynamics often must rely on weak environmental excitation sources acting on bridges and attempt to extract modal parameters from low SNR response data. The selected identification algorithm ability to capture the vibrational signal characteristics from those relatively low SNR data is critical to the mode identifiability as well as the accuracy of modal properties. Thus, good understanding of the actual capabilities of different OMA techniques when dealing with bridge response induced by weak environmental excitation sources is required for successful adoption of OMA under such circumstances.

The main objective and contribution of this paper is to obtain an insight into the capabilities and, conversely, limitations of OMA when applied to field exercises with low SNRs. The opportunity of a suitable low SNR scenario presented itself during ambient vibration testing of a concrete motorway off-ramp bridge with 11 short to medium continuous spans and subjected to only weak excitations with responses measured using affordable measurement technology, which however could be prone to noise. The bridge was closed to traffic, and so during data collection it was only excited by traffic on a motorway passing underneath and on several on- and off-ramp bridges located nearby, weak to moderate winds and possible micro tremors. The sensors were 46 stand-alone MEMS accelerometers/recorders. As modal parameter identifiability often depends on the system identification algorithms adopted, performance of three OMA techniques, namely the PP, FDD and data-driven SSI, was evaluated in the low SNR in-situ application exercise.

The methodological steps involved planning an experimental programme and sensor layout on the bridge, which were assisted by a finite element (FE) model of the structure, collecting and pre-processing the data, estimating noise sensor floor, implementing the different modal parameter identification techniques, comparing the quality and agreement of OMA results from the different methods including natural frequencies, damping ratios and mode shapes, and, finally, comparing the experimental modal properties with those determined numerically from the FE model.

The paper first describes the bridge structural system and its major non-structural elements to contextualise the case study, and how they were conceptualised to prepare an FE structural model to assist with test planning and interpretation of experimental results. Then, the details of the experimental programme