Engineering Structures 165 (2018) 50–62

Contents lists available at ScienceDirect

Engineering Structures

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

Operational modal analysis of an eight-storey building with asynchronous data incorporating multiple setups

Yi-Chen Zhu*, Yan-Long Xie, Siu-Kui Au

Institute for Risk and Uncertainty and Centre for Engineering Dynamics, University of Liverpool, United Kingdom

ARTICLE INFO

Keywords:
Asynchronous data
Bayesian methods
Full-scale tests
Operational modal analysis

ABSTRACT

This paper presents operational modal analysis of an eight-storey concrete building using ambient vibration data collected in an 'asynchronous' manner, i.e., different sensors using possibly different clocks for data sampling. Five force-balance accelerometers were used with a number of setups to cover all locations of interests. Modal identification is performed using a Bayesian frequency domain method for asynchronous data and the global mode shape is assembled using the global least square method. The identified modal parameters based on asynchronous data are evaluated by comparing with those identified based on synchronous data. The identification uncertainties of modal parameters are investigated through the posterior coefficient of variation in a Bayesian context. The study provides insights into the challenges encountered when using asynchronous data for operational modal analysis in a practical context.

1. Introduction

Structural health monitoring (SHM) has the general objective of monitoring the physical conditions of structures with potential applications in detecting damage during their service life [1–5]. Various means for SHM have been proposed in the past few decades by measuring structural response such as strain, displacement and acceleration. Modal identification aims at identifying the modal properties involving natural frequencies, damping ratios and mode shapes based on the measured structural response data. It is often the first step in SHM that provides the baseline information on the current state of the subject structure [6–9].

For civil infrastructures which are typically large-scale, operational modal analysis (OMA), also known as ambient modal identification, has been widely used. It can be conducted when the structure is under environmental excitations such as wind, cultural activities and microtremor without artificial loading conditions. In OMA, the excitation is unknown but assumed to be 'broadband random'. Due to its high economy and feasibility, OMA has attracted great attention in both theory development and real applications in recent years [10–12]. It provides important information for downstream applications such as finite element model updating [13–17].

In full-scale tests, mode shape information is often demanded where the vibration response at multiple locations needs to be measured. Due to the limited number of instruments or difficulties in their deployment, it often happens that the interested DOFs (degrees of freedom) cannot be all measured in a single setup. In this case, a common strategy is to conduct multiple setups covering different DOFs in each setup with some reference DOFs in common [18–22]. Conventionally, the modal parameters in individual setups are identified separately using single-setup modal identification methods and the global mode shape is assembled from the local ones identified in different setups. Assembly techniques have been developed where the global mode shape is determined as the one that minimises the discrepancies between local mode shapes in different setups in a least square sense [23,24]. OMA method incorporating multiple setups have also been developed in both non-Bayesian [25] and Bayesian [26] context. Multiple-setup algorithms have also been applied to structural modal updating [27,28].

Time synchronisation is another issue which should be considered in real implementations. Conventional OMA approaches assume that the digital data from different channels in each setup are synchronised, i.e., sampled based on the same time scale. Simply recording the data from multiple channels with the same duration does not imply that they are synchronised. The sampling pace in different sensors needs to be real-time controlled by a synchronisation protocol. Transmitting analogue data from sensors directly to a central synchronisation console requires long cables, with implications on logistics, voltage drop and noise. Alternative options exist, e.g., Network Time Protocol [29], Global Positioning System [30] and wireless sensor networks [31–33], requiring varying degrees of communication infracture on site. If modal identification can be performed for asynchronous data, field tests can be conducted in a more economical and flexible manner compared to

---

* Corresponding author at: Harrison Hughes Building, Brownlow Hill, Liverpool L69 3GH, United Kingdom.
E-mail addresses: sgyzhu7@liverpool.ac.uk (Y.-C. Zhu), yanlong.xie@liverpool.ac.uk (Y.-L. Xie), siukuiau@liverpool.ac.uk (S.-K. Au).

https://doi.org/10.1016/j.engstruct.2018.03.011
Received 2 July 2017; Received in revised form 5 March 2018; Accepted 6 March 2018

synchronous data. However, lower identification quality is expected because less information is available.

This paper investigates the quality of modal identification results based on asynchronous ambient data incorporating multiple setups in full-scale tests. An eight-storey concrete building is used as a vehicle for investigation, where complication and practical aspects in field implementation are naturally reflected in the data. Bayesian OMA methods assuming synchronous [34] or asynchronous data [35,36] are applied to the data of each setup individually. The global mode shape is assembled from the most probable local mode shapes in individual setups based on the global least square method [23]. The quality of identified modal parameters based on asynchronous data is compared against their synchronous counterpart. In addition to the most probable value, identification uncertainties associated with the modal parameters are also discussed for both synchronous and asynchronous cases. This work provides an opportunity to investigate the effect of asynchronous data in OMA under full-scale test configurations. Practical issues with time synchronisation and challenges encountered in real applications are also discussed.

This paper is organised as follow. The basic properties of the tested building are presented in Section 2. Section 3 provides detailed information about the field instrumentation. The modal identification methods used in this work are briefly reviewed in Section 4. The identification results and posterior uncertainties are investigated in Section 5. The work is concluded in Section 6.

2. Description of field structure

Brodie Tower is a reinforced-concrete building situated on the campus of the University of Liverpool (Fig. 1). It has eight storeys with a total height of approximately 25 m. The ground floor of the building is connected to another office building (Muspratt Building, see Fig. 1). From 1/F to 7/F, the floor slabs are T-shaped spanning over a $25\ \text{m} \times 28\ \text{m}$ area; see Fig. 2, where sensor locations are discussed later in Section 3.2. The ground floor of the building is used as a social space and the remaining floors are mainly office and lecture rooms.

3. Instrumentation

Five force-balance triaxial accelerometers were deployed to measure the ambient vibration of the structure. The equipment for each sensor location comprises accelerometer, GPS receiver, high-precision clock, battery and accessories (e.g., cables). These are hosted in a waterproof rugged case in-house designed for mobile field deployment, see Fig. 3.

Analogue voltage signals of acceleration were acquired by a 24-bit data logger at a sampling rate of 50 Hz. The noise level of the accelerometers is about $0.1\ \mu g/\sqrt{\text{Hz}}$ in the frequency band above 1 Hz. In each setup, the acceleration data comprises $5 \times 3 = 15$ channels for twenty minutes.

Fig. 1. Brodie tower.

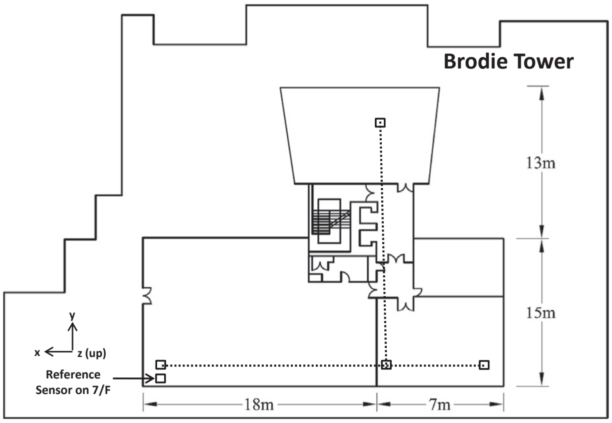

Fig. 2. Floor plan with sensor locations.

3.1. Sensor locations

In view of the floor plan in Fig. 2, it was intended to obtain a mode shape that resolves into the 'T-shape'. Compromising with the available number of sensors, four locations on each floor from 1/F to 7/F with one reference location on 7/F were measured, giving $(4 \times 7 + 1) \times 3 = 87$ degrees of freedom (DOFs) in total. For feasibility and convenience in alignment, the sensors were located in the corridors and they were oriented along the frame direction of the building.

3.2. Reference sensor

Due to the limited number of sensors, only 5 locations (15 DOFs) can be measured in a single setup. Multiple setups are thus necessary to cover all the 29 locations (87 DOFs) of interest. The mode shapes identified in different setups are under different scaling and it is necessary for different setups to share some 'reference DOFs' so that their 'local mode shapes' can be assembled into a 'global mode shape' comprising the DOFs measured in all setups. The data at the reference DOFs should contain significant responses of all the modes of interest (i.e., avoid nodal locations). In this test, one reference sensor was placed in all setups on 7/F near the lower left cover of Fig. 2. That location was expected to have significant vibration response and was unlikely to be a node.

3.3. Roving setups

To cover the DOFs in Fig. 2, the remaining four sensors were 'roved' to different floors in different setups, leading to seven setups. In order to investigate the effect of imperfect synchronisation on modal identification, ideally it would be desirable to have two sets of data, one synchronous and the other asynchronous, during exactly the same time period. Due to the limited number of sensors and the impossibility of placing two sensors at exactly the same location, this was not feasible, however. As a practical alternative, asynchronous data was collected first, followed by synchronous data.

The setups for asynchronous data were conducted (i.e., each sensor sampled the data using its own clock) in the morning from 8:30 to 12:30 in the order of 7/F to 4/F, 2/F, 3/F and 1/F. The setup on 3/F was conducted after the one on 2/F as there was an examination in the lecture room on 3/F at that time. After the setups for asynchronous data, all the sensors were synchronised using 'real-time' clocks (see details in Section 3.4). The setups for synchronous data were then conducted in the afternoon from 14:30 to 17:10 with the order from 7/F to 1/F. Fig. 4 shows a schematic diagram of the setup plans and the measured DOFs of Setup 3 (i.e., 5/F) for synchronous data.