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Bayesian operational modal analysis and Markov chain Monte Carlo-based model updating of a factory building

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ABSTRACT

This paper presents the results of a full-scale ambient vibration test, modal analysis and model updating of a typical 14-story reinforced concrete factory building in Hong Kong. A 12-setup test was conducted in the building's three staircases using six tri-axial accelerometers. The modal parameters of each setup were identified following the Bayesian approach and the partial mode shapes from different setups were assembled using the least-squares method. The factory building was then modeled as a shear building and the Markov chain Monte Carlo (MCMC)-based Bayesian model updating method was applied utilizing the identified modal parameters to determine the probability density functions of the various inter-story stiffness values. Four classes of shear building models were studied and the MCMC-based Bayesian model class selection was developed to identify the most plausible model class. The identified modal parameters and model updating results were analyzed and are discussed in detail. This study provides valuable experience and information for the future development of the structural model updating and structural health monitoring of building systems.

1. Introduction

Modal analysis and model updating based on field test vibration data are of long-standing interest among engineers and researchers working in the field of structural health monitoring (SHM). They are often applied to monitor the safety and serviceability of structures. Years of development have resulted in considerable improvements in both test equipment and the efficiency of vibration test methods. Full-scale ambient and forced vibration measurements have been used for decades to identify the dynamic characteristics of real structures [1]. Compared with the ambient vibration test, the forced vibration test usually requires a large excitation force to produce detectable responses. The ambient vibration test has, on the other hand, proved over the years to be more convenient and economical to perform than the forced vibration test. The main advantage over the forced vibration test is that it requires only light equipment and fewer workers. Ambient vibration sources include wind, microtremors, microseisms, pedestrians and vehicular traffic. Ambient vibration tests of full-scale structures are of considerable importance in obtaining the dynamic properties of those structures.

Modal analysis is considered the most important step in helping engineers to determine the dynamic properties of structures, and its results can be used for model updating and then damage detection [2–13]. The aim of modal analysis is to identify such modal parameters as natural frequencies, mode shapes and modal damping ratios from measured time-domain data such as acceleration responses. Beck and Katafygiotis [14,15] developed the Bayesian framework to identify structural dynamic systems. The main objective is to determine the joint posterior probability density function (PDF) of the uncertain model parameters. Yuen and Katafygiotis [16] extended the Bayesian framework for modal identification using the fast Fourier transform (FFT) of ambient time-history data, and successfully applied it to several simple systems. One shortcoming of the method in [16] is its limited applicability to large-scale structures with a large number of degrees of freedom (DOFs). Based on previous work, Au [17,18] developed a fast version of the modal analysis method proposed by Yuen and Katafygiotis [16]. Instead of considering all modal parameters (including natural frequency, mode shape, modal damping ratio, spectral density of the modal force and spectral density of the prediction error) simultaneously as minimization variables, Au [17,18] extracted the mode shapes from the set of minimization variables, thereby significantly reducing the amount of computational time required. As a result,

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the method can be applied to systems with a large number of measured DOFs.

Structural model updating is an important approach to correcting the model parameters of finite element models utilizing a set of measured vibration data, ensuring that the model-predicted responses are well-matched to the measured responses. The results of structural model updating are important for engineers to accurately model similar types of structures in the future. Updated numerical models can be used in numerous engineering fields (e.g., structural vibration control, force identification, vehicle load identification of bridge systems and structural damage detection). Beck [14] introduced the Bayesian statistical system identification framework. Work in the early stage focused primarily on identifiable cases. In situations in which the number of uncertain parameters is large and the number of measured data points is small, the degree of uncertainty associated with some or all identified parameters will be high. When the uncertainty of one or more parameters becomes too great, the model updating problem is considered unidentifiable [19]. Based on previous work, Katafygiotis [19] modified the Bayesian probabilistic model updating method to deal with unidentifiable cases under conditions of limited measured information. Lam et al. [4] extended the Bayesian updating method, and successfully applied it to the model updating of a coupled-slab system. To deal with the unidentifiable problem, Beck and Au [20] proposed a multiple-level Markov chain Monte Carlo (MCMC) model updating method following the idea of simulated annealing, which is adopted in model updating in the literature [21,22]. Later, Lam et al. [5] extended the method in [20] by constructing a bridge PDF at each sampling level that finally converged to the target posterior PDF in a controlled manner, and they then applied it to solve the model updating problem of a complicated three-dimensional (3-D) structure [23].

There are two main difficulties in the Bayesian model updating, they are (1) finding the important region of the posterior PDF in the high-dimensional parameter space, and (2) evaluating the high-dimension integrals in order to quantify the posterior uncertainties. The proposed method circumvents these two difficulties by drawing samples from the posterior PDF using MCMC in multiple levels. During the process, the bridge PDFs are updated level by level according to the posterior PDF. A recently developed stopping criterion was used to ensure the convergence of the sampling process. Based on the proposed method, the posterior PDF can be obtained efficiently.

This paper presents the results of a comprehensive study comprising the ambient vibration testing, modal analysis and MCMC-based model updating of a 14-story reinforced concrete building. It is essential that the dynamic properties of aging structures are explored after decades of service time. The ambient test in this study was conducted in the building's three staircases. Due to a limited number of sensors, multiple-setup tests were planned to cover all measurement locations. To obtain the modal parameters of the factory building, a fast Bayesian FFT method [17,18] was adopted. To determine the vertical distribution of its inter-story stiffness, three independent shear building models were used (two for translational vibration and one for torsional vibration). Finally, based on the identified modal parameters, the MCMC-based Bayesian method was applied to update the shear building models.

One of the main contributions of the paper is the new derivation of formulations in calculating the evidence of model classes utilizing the set of MCMC samples. By doing this, the inherent uncertainties in the model updating problem can be explicitly considered in the model class selection process. Since the MCMC samples of uncertain parameters can be used directly, the model class selection process becomes efficient and simple.

2. Ambient vibration test

2.1. Description of the building and equipment

The target factory building is a 14-story reinforced concrete structure. Fig. 1(a) shows the overall appearance of the building. The factory building is not an isolated structure, it is rigid connected with the adjacent building from G/F to 4/F in the right


(a)

(b)

Fig. 1. Target factory building: (a) front view and (b) connection with adjacent building.