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Statistical analysis of modal parameters of a suspension bridge based on Bayesian spectral density approach and SHM data

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ABSTRACT

Uncertainty of modal parameters estimation appear in structural health monitoring (SHM) practice of civil engineering to quite some significant extent due to environmental influences and modeling errors. Reasonable methodologies are needed for processing the uncertainty. Bayesian inference can provide a promising and feasible identification solution for the purpose of SHM. However, there are relatively few researches on the application of Bayesian spectral method in the modal identification using SHM data sets. To extract modal parameters from large data sets collected by SHM system, the Bayesian spectral density algorithm was applied to address the uncertainty of mode extraction from output-only response of a long-span suspension bridge. The posterior most possible values of modal parameters and their uncertainties were estimated through Bayesian inference. A long-term variation and statistical analysis was performed using the sensor data sets collected from the SHM system of the suspension bridge over a one-year period. The t location-scale distribution was shown to be a better candidate function for frequencies of lower modes. On the other hand, the burr distribution provided the best fitting to the higher modes which are sensitive to the temperature. In addition, wind-induced variation of modal parameters was also investigated. It was observed that both the damping ratios and modal forces increased during the period of typhoon excitations. Meanwhile, the modal damping ratios exhibit significant correlation with the spectral intensities of the corresponding modal forces.

1. Introduction

Vibration-based structural health monitoring (SHM) techniques have become valuable methods for evaluating structural integrity, and reliability throughout the life-cycle of structures. The SHM techniques are often based on modal parameters such as natural frequencies, damping ratios and mode shapes [1]. However, in field conditions, when structures are subject to changing environmental conditions, the modal parameters of the structure exhibit non-stationary behavior [2–4]. Meanwhile, since the ambient vibration and operational conditions such as wind and traffic may affect the measured signals, the identified modal parameters will exhibit uncertainties. Therefore, the modal parameters identification methods need to provide estimation of the parameter uncertainty.

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During the past few decades, modal identification of civil engineering structures based on ambient vibration measurements has been widely investigated, and a variety of output-only modal identification methods have become available in both time and frequency domains [5]. Among the frequency domain methods, the peak picking (PP) and frequency-domain decomposition (FDD) techniques are most widely used [6]. Although many methods are available in literature for identification of modal parameters, there are relatively few studies on the statistical bounds of the identified parameters [7]. While time domain methods have some advantages in identifying the closed modes and damping ratios, they have some drawbacks. The advantage of stochastic subspace identification (SSI) methods is that they are numerically robust and non-iterative. However, most of SSI algorithms do not provide any direct estimation of the variance of the identified modal parameters [7].

Bayesian inference provides a promising and feasible identification solution for the purpose of structural health monitoring. The Bayesian approaches offer a powerful tool for system identification that explicitly addresses uncertainty. A significant advantage of the Bayesian inference is that not only the optimal estimates can be determined but also their associated uncertainties can be quantified in the form of probability distributions [8]. Recently, there is a rising interest in computing the uncertainties of modal parameters using the Bayesian approaches including the Bayesian spectral density approach (BSDA) [9], Bayesian time domain approach, and Bayesian FFT approach [10–12]. These methods provide rigorous means for obtaining modal properties as well as their uncertainties for given measured data and modeling assumptions. Although there exist many Bayesian approaches, computational difficulty has severely hindered their wider applications. In [11], a two-stage fast Bayesian Spectral Trace Analysis (BSTA) method is developed, which can address the computational challenges of the conventional Bayesian approach. In the BSTA method, the interaction between the spectrum variables (i.e., frequency, damping ratio as well as the spectral density of modal excitation and prediction error) and the spatial variables (i.e., mode shape components) can be decoupled completely. Although the theory and computational methods provide a rigorous and viable platform, practical and important issues regarding data limitation, interpretation of results, trade-off between identification precision and modeling error risk need to be addressed for application of the Bayesian spectral density approach in real structures [13].

In the case of bridges, environmental factors such as temperature, wind profile and traffic are known to increase the variance of a modal frequency. The influence of varying environmental conditions on structural modal properties has been extensively investigated through field measurements and dynamic tests [14–17]. Results from monitoring of the Humber Bridge showed that the temperature and the wind were the two most significant influences on the bridge behavior [18]. Several studies have shown that operational modal parameters obtained using vibration-based structural monitoring systems are not fixed and can vary within 5% of their range from their mean value [2,15]. However, the relationships between the modal frequencies and the environmental and loading effects (e.g. temperature, wind, traffic) are complex. In [19], it was observed that the dynamic behavior of the suspension bridges is dependent on the magnitude of the environmental effects. For instance, the fundamental frequency of a suspension bridge reduces as the wind speed increases. On the other hand, the modal damping increases when the wind velocity increases and exceeds a certain level. According to long term observation and estimation results of the operational modal parameters, the uncertainty distributions of these parameters can be fitted by normal distributions [20]. Although a lot of field measurements and observations were conducted regarding the relation between the modal frequency and the environmental influences, very few studies addressed the statistical distribution over a long period time. Moreover, the variation of damping parameters was rarely studied.

This paper presents a statistical analysis for the modal parameters of the Runyang Suspension Bridge (RSB) based on its SHM data. RSB is a long-span suspension bridge constructed in 2005 over Yangtze River, China. Since 2005, a long-term structural monitoring system installed on the bridge provides large data sets. As there are a large amount of data sets recorded by the SHM system of the bridge, a robust and automatic identification method is necessary. To process large data sets for the long-term structural monitoring system, the Bayesian spectral density algorithm is adapted to address the uncertainty of modes extraction from output-only response. Furthermore, the extraction of modal parameters is fully automated by introduced the Bayesian spectral trace analysis method, which can address the computational difficulties of conventional BSDA. Moreover, statistical studies of the operational modal parameters over a long-term period were conducted to study the parameter distributions and variation. In addition, a period data sets during a strong wind excitation is presented to research the wind-induced variation of modal parameters.

2. Bayesian spectral density approach for output-only modal identification

2.1. Dynamics of linear systems

Consider a linear dynamic system with N_d degrees of freedom and equation of motion:

$$\boldsymbol{M}\ddot{x}(t) + \boldsymbol{C}\dot{x}(t) + \boldsymbol{K}x(t) = \boldsymbol{T_0}\boldsymbol{W}(t) \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are the mass, damping and stiffness matrix, respectively; $\boldsymbol{T}_0$ is a force distributing matrix. The external excitation $\boldsymbol{W}$ can be modeled as zero-mean Gaussian white noise with spectral intensity matrix $\boldsymbol{S_W}(\omega) = \boldsymbol{S_{W0}}$.

Using modal analysis, one obtains the uncoupled modal equations of motion:

$$\ddot{\boldsymbol{q}}_{r(t)} + 2\xi_r\omega_r\dot{\boldsymbol{q}}_{\boldsymbol{r}}(t) + \omega_r^2\boldsymbol{q}_{\boldsymbol{r}}(t) = \boldsymbol{w}_{\mathbf{r}}(t), \quad r = 1, \ldots, N_d \tag{2}$$