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Fast Bayesian approach for modal identification using forced vibration data considering the ambient effect

Yan-Chun Ni [a], Feng-Liang Zhang [b,*]

[a] Department of Bridge Engineering, Tongji University, China
[b] Research Institute of Structural Engineering and Disaster Reduction, Tongji University, China

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ABSTRACT

Modal identification based on vibration response measured from real structures is becoming more popular, especially after benefiting from the great improvement of the measurement technology. The results are reliable to estimate the dynamic performance, which fits the increasing requirement of different design configurations of the new structures. However, the high-quality vibration data collection technology calls for a more accurate modal identification method to improve the accuracy of the results. Through the whole measurement process of dynamic testing, there are many aspects that will cause the rise of uncertainty, such as measurement noise, alignment error and modeling error, since the test conditions are not directly controlled. Depending on these demands, a Bayesian statistical approach is developed in this work to estimate the modal parameters using the forced vibration response of structures, simultaneously considering the effect of the ambient vibration. This method makes use of the Fast Fourier Transform (FFT) of the data in a selected frequency band to identify the modal parameters of the mode dominating this frequency band and estimate the remaining uncertainty of the parameters correspondingly. In the existing modal identification methods for forced vibration, it is generally assumed that the forced vibration response dominates the measurement data and the influence of the ambient vibration response is ignored. However, ambient vibration will cause modeling error and affect the accuracy of the identified results. The influence is shown in the spectra as some phenomena that are difficult to explain and irrelevant to the mode to be identified. These issues all mean that careful choice of assumptions in the identification model and fundamental formulation to account for uncertainty are necessary. During the calculation, computational difficulties associated with calculating the posterior statistics are addressed. Finally, a fast computational algorithm is proposed so that the method can be practically implemented. Numerical verification with synthetic data and applicable investigation with full-scale field structures data are all carried out for the proposed method.

1. Introduction

In-situ structural vibration testing has improved significantly due to the great development of modern technology, such as sensor and data acquisition systems. All these make it possible to measure the structure response with enough quality. It

* Corresponding author.
E-mail address: fengliangzhang@tongji.edu.cn (F.-L. Zhang).

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is the most direct method to obtain data from real structures after construction or track the property during the construction process. Based on these data, modal identification is performed to obtain the value of modal parameters. This has attracted enormous attention all over the world and played an essential role in assessing the current or future performance of the structures efficiently [1], for example model updating, damage detection, structural response calculation and structural health monitoring [2–11]. The modal parameters mainly include natural frequency, damping ratio, mode shape and other parameters depending on different cases and requirements [12–15]. The common types of tests to collect the dynamic data are ambient, forced and free vibration tests. In these three tests, the ambient vibration test is the most economical one due to the excitation style, which needs no artificial excitation and the measurement is under normal working conditions [16–22]. Consequently, the signal-to-noise (S/N) ratio in this kind of test is not as high as those in forced and free vibration tests, since the excitation is not under control. For the second one, i.e., forced vibration test, special equipment is required to input the artificial known excitation into the structure during the test [23–26]. Due to the participation of the excitation equipment, a relatively high S/N ratio is available and the collected vibration data has a good quality for the next step of analysis. Free vibration is the one which satisfies the theory best. Although the information of the excitation is not needed during analysis, artificial excitation is also carried out to excite the whole structure to make it under free vibration conditions.

Due to the development of vibration tests, more accurate results and more reasonable assumptions are required in the modal identification approach. For forced vibration test, there are already some existing methods used for the identification. The most simple one is named the half-power bandwidth method [27,28], which is very easy to learn although its accuracy is the lowest. There are also some sophisticated methods, such as circle fitting method [29], the Ewins-Gleeson method [30], the complex mode indication function method [31,32], Rational fraction polynomial method (also called orthogonal polynomials) [33,34], the global RFP method, Polyreference frequency domain method [31,35], etc. No matter whether simple or complicated, for these traditional methods, they provide only the identification of most probable values (MPVs), not the posterior uncertainty. The remaining uncertainties of modal parameters are becoming more important in modern structural health monitoring and uncertainty propagation [36–42]. A rigorous quantification of the uncertainty is necessary to improve the development of modal identification.

In forced vibration field tests, the measured data mainly comprises three parts, forced vibration response, measurement noise and ambient vibration response. Existing modal identification methods often assume the first two components dominate the measured data and the effects of the last component are usually ignored. However, ambient vibration will cause modeling error and influence the accuracy of the identified results. This is especially obvious in the higher modes which need more energy for excitation. On the other hand, the measured data also exhibits a variety of spectral characteristics over its measurement bandwidth, many of which are irrelevant to the mode to be identified or difficult to model [43,44,45]. Therefore, careful choice of assumptions in the identification model is required and fundamental formulation needs to be developed to account for the associated uncertainty. Otherwise significant bias or conclusions inconsistent with structural dynamics may result. Depending on this demand, a robust system identification approach is needed to offer a fundamental means for extracting the information about modal parameters and the associated posterior uncertainty from noisy data considering ambient vibration effects.

In this work, a Bayesian approach for forced vibration data considering the ambient vibration effect is developed, which is a frequency domain method using the Fast Fourier Transform (FFT) of the raw data. A posterior probability density function (PDF) is formulated including all the parameters of interest and used for the next step of optimization to identify the MPV of modal parameters. Difficulty is met in brute optimization and then a proper strategy is carried out to solve the difficulties. A well-separated mode case is focused on in the paper, which is the common case in reality. A fast algorithm is developed, which can identify the parameters effectively, even for a large number of measured degrees of freedom (DOFs). Synthetic example is designed to verify the proposed method. After that, based on shaker tests carried out on a full-scaled footbridge, the dynamic characteristics of the field structure are analyzed in detailed by applying the proposed method.

2. Bayesian FFT modal identification

When a structure is excited by a known artificial load, it will vibrate according to the style of the input. Besides this dominant excitation, there will also be ambient excitation due to disturbance from the environment all the time, and then the responses acquired will include both forced vibration response $\ddot{\mathbf{x}}_{\mathbf{f}j} \in R^n$ (acceleration in this case; n denotes the number of measured DOFs) due to the artificial excitation and ambient vibration response $\ddot{\mathbf{x}}_{aj}$. Considering prediction error $\boldsymbol{\varepsilon}_j$ simultaneously to represent the discrepancy between the measured and theoretical model responses, the measured response can be given as follows:

$$\hat{\ddot{\mathbf{x}}}_j = \ddot{\mathbf{x}}_{fj} + \ddot{\mathbf{x}}_{aj} + \boldsymbol{\varepsilon}_j \tag{1}$$

where $j = 1, \ldots, N$ with N being the number of sampling points. Converting the data from the time domain to frequency domain, the FFT of $\hat{\ddot{\mathbf{x}}}_j$ can be defined as:

$$\hat{\mathscr{F}}_k = \sqrt{\frac{2\Delta t}{N}} \sum_{j=1}^{N} \hat{\ddot{\mathbf{x}}}_j \exp\left[-2\pi\mathbf{i}\frac{(k-1)(j-1)}{N}\right] \quad (k = 1, \ldots, N) \tag{2}$$