Preliminary Experiments of a Structural Health Monitoring Method with an Accurately Controlled Small Vibrator and Wireless Sensor Networks

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Summary

This paper shows a structural health monitoring method based on artificially induced vibration response measurements. The method utilizes an accurately controlled small vibrator and multiple wireless sensors, and is capable of precisely measuring frequency response functions in a specified frequency band. The paper shows a design of the instruments and a structure estimation procedure which utilizes the above mechanical system. The procedure is based on the structural analysis of the linear N-degree-of-freedom system and formalizes the task as a maximum likelihood estimation problem. The effectiveness of the method is verified by a numerical simulation with a simple model, and its usability and limits are discussed.

Keywords: accurately controlled small vibrator; wireless sensor network; structural health monitoring.

1. Introduction

Structural health monitoring (SHM) of infrastructures is recognized as a very important task in advanced nations and have been conducted in many ways, visual inspection, tap testing, electromagnetic testing and so on. Among those, a vibration response measurement is one of the most frequently used method since the response can be used as a metric of extent of damages in a structure. This paper shows a SHM method based on vibration response measurements utilizing an accurately controlled small vibrator and multiple wireless sensors. The behaviour of those is properly-synchronized, and therefore the whole system is capable of precisely measuring frequency response functions (FRFs) in a specified frequency band. We also show a structure estimation method which utilizes the above sensing system. The method is based on the structural analysis of the linear N-degree-of-freedom system and formalizes the task as a maximum likelihood estimation problem. The effectiveness of the proposed method is verified by a numerical simulation in which a simple mass-spring-damper system is used as a target of estimation.

2. Structural estimation method

The SHM method proposed in this paper utilizes an artificially induced vibration and record vibration response at multiple points in a structure to be monitored. The vibrator and the sensors are directly attached to the structure, and measure a band-limited FRF at each sensing point. We formalized a structural estimation problem using the data based on the direct parameter identification technique of N-degree-of-freedom (DOF) system.

The unknown parameter $\boldsymbol{\theta}_j = \begin{bmatrix} m_j & c_j & k_j \end{bmatrix}^T$ ($j = 1, 2, \cdots, N$) in the system can be determined by optimizing the following function.

$$\sum_{\omega\subset\Omega}\{\mathbf{F}'_{\delta}(\omega)-\mathbf{\Phi}'(\omega)\mathbf{\theta}\}^{T}\{\mathbf{F}'_{\delta}(\omega)-\mathbf{\Phi}'(\omega)\mathbf{\theta}\}\rightarrow \min \qquad \text{s.t.} \quad \mathbf{\theta}\geq 0 \qquad (1)$$

$\Omega=\{\omega_1,\omega_2,\cdots,\omega_W\}$ is a set of measuring frequencies, $\mathbf{F}_{\delta}(\omega)$ is a normalized force vector which represents an excitation point and $\mathbf{\Phi}'(\omega)$ is a coefficient matrix constructed from the measured FRF data. For details, please refer to the full paper.

3. Numerical experiment

In order to verify the applicability of the estimation method, we conducted a numerical experiment with a simple 7-DOF system with two fixed points. Fig. 1 shows an example of estimated mode shapes. The first order natural frequency and corresponding mode shape are comparably well estimated. Estimation of higher order modes, however, requires more accurate FRF data. Possible reasons are that the measuring frequencies Ω only follow the first order natural frequency and that an amplitude of higher order mode is comparably small. Fig. 2 shows a comparison between a true FRF and an estimated one. Estimated FRF in measuring frequency band (4.6 - 5.5Hz) fitted well to the true function while its accuracy decreased with distance from the band.

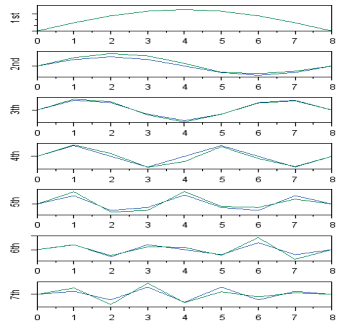

Fig. 1: Example of estimated mode shapes (true in blue and estimated in green)

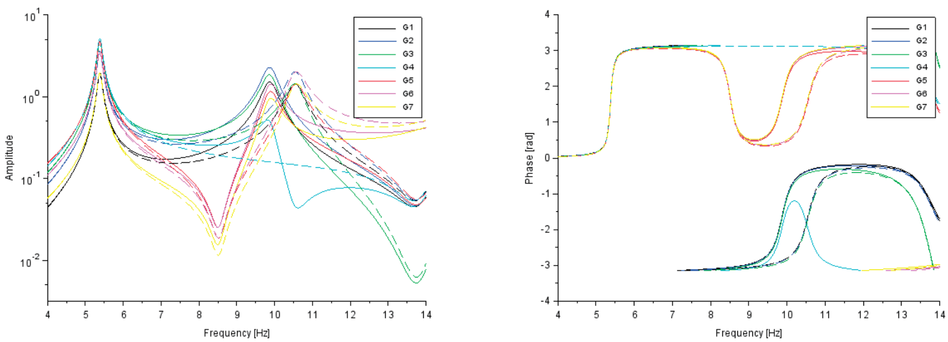

Fig. 2: An estimated FRF (estimated FRF in solid line and true in dashed line)

4. Conclusion

In this paper, we briefly explained the vibration response sensing system and conducted a numerical experiment of a SHM method based on the direct parameter identification technique. The experimental result showed that the method is applicable to estimate modal properties, natural frequencies and mode shapes. Furthermore, it revealed that to precisely identify physical properties in the structure requires very accurate FRF data while modal properties are comparably easily estimated. These perceptions may also be helpful in the actual SHM scene.

The paper only shows the results of a preliminary experiment and further extensive investigation is required. Future work includes comprehensive survey of tendencies of estimation under various structural models and measuring settings. In particular, to find a proper condition of measuring is important since it may drastically improve accuracy of estimation at a lower cost. Furthermore, a performance evaluation experiment with actual structures should be conducted.