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Laboratory experiment of the structural sensing method using the accurate artificial vibrator

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ABSTRACT

This paper presents a structural sensing method using the accurate artificial vibrator and shows the results of vibration experiments in laboratory scale. The accurate artificial vibrator generates harmonic forces by rotating an eccentric mass. Since the rotation is accurately controlled by means of a phase control type servomotor, the vibrator generates accurate harmonic forces periodically. The phase information obtained from the servomotor let us calculate the force function precisely. Applying Auto-Regressive eXogenous (ARX) model to the time series of force function and measured displacement responses yields the Green function of a target structure. In this research, we investigated the performance of prototype system and developed the Green function estimation method. We also conducted laboratory scale vibration tests in which the prototype system was applied to a two-meter simple beam. The estimated Green function was simulated by the analysis of Finite Element Method (FEM) and its structural model was successfully determined.

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1. Introduction

Deterioration of civil infrastructures is recognized as an important problem in advanced nations. It is considered unrealistic to reconstruct all of aged civil infrastructures for financial reason. Therefore, maintenance and management of civil infrastructures are needed to decrease their life cycle cost. In order to maintain civil infrastructures effectively, it is important to assess their current condition quantitatively. Therefore, various Structural Health Monitoring (SHM) systems have been studied by many researchers [2,4,5,24].

Vibration-based damage detection method might be a possible solution to estimate health condition of civil infrastructure, because natural frequencies, modal damping factors, mode shapes and also frequency response function reflect the mechanical condition such as the stiffness and boundary condition. One of the important issues of the vibration-based damage detection is variations of dynamic characteristics due to a temporal change of environmental condition [5]. Ambient vibration, which may be excited by a traffic or wind, is analyzed to estimate vibration characteristics in many studies. In general, ambient vibration is assumed as white even though it depends on the source and then varies in case. Therefore, it is considered difficult to detect a small change of vibration characteristics accurately when the ambient vibration is analyzed. Therefore, an artificial vibrator, which is able to generate very accurate and stable forces, is needed.

Other important issue of vibration based damage detection is the limitation of the number of sensors [2]. However, in recent years, wireless sensor network is intensively studied in a research field of SHM to integrate an efficient monitoring system which allows us to deploy a number of sensors to a target structure. Wireless sensor network is a system consisting of a server (coordinator) and many sensor nodes (end devices) which have a radio communication module, physical sensors, a Micro-Processor Unit (MPU), and a small battery. This system enables us to decrease the installation and maintenance costs of SHM system and also to deploy many sensors to a target structure in high spatial resolution.

The authors have been developing a structural sensing system using the accurate artificial vibrator and wireless sensor network [11]. In this system, the accurate artificial vibrator generates harmonic forces and vibrates a target structure periodically. The wireless sensor nodes measure the acceleration responses as synchronizing with the vibrator. Because the excited forces are very accurate and stable, the Green functions of a target structure are accurately estimated. And also, measuring the responses at

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many points with the wireless sensor network provides a great quantity of information. The accurate Green functions obtained at many measuring points may improve accuracy and spatial resolution of damage detection.

The objective of this research is to demonstrate that the proposed method is able to estimate the Green function of a target structure very accurately. In this research, we first investigated the performance of prototype system and described a mathematical model of displacement response excited by the accurate artificial vibrator using Auto-Regressive eXogenous (ARX) model. We also carried out basic vibration tests in laboratory scale for demonstration of the present method. In the experiment, a prototype of the accurate artificial vibrator was applied to a two-meter simple beam supported by roller bearings. The displacement response was measured using wireless sensor nodes and a laser displacement meter. Analyzing the time series of displacements and force function with ARX method yields the Green functions from an excitation point to sensors. The Green function obtained from the laboratory scale experiment was successfully simulated by Finite Element Method (FEM) analysis.

2. Previous research

Structural health monitoring is performed to determine the location and severity of damage in a civil infrastructure. Various methods are proposed by many researchers. In general, these methods can be classified as local-damage detection method and global-damage detection method [24]. Local-damage detection methods are conducted to determine the exact location and extent of the damage like a crack in a part of damaged structure. On the other hand, global-damage detection methods detect damage throughout the whole structure by investigating spatial or temporal variation of vibration responses [4]. This paper focuses on the global-damage detection method. A review of papers related to the vibration-based global structural health monitoring can be found in Doebling et al. [5], Chang et al. [4], Carden and Fanning [2], and Yan et al. [24].

Global-damage detection methods can be further classified as methods based on the dynamic characteristics of structure and methods based on online measured response signal of structure [24]. One of the former examples is model updating. This method adjusts the analytical mass and stiffness matrices of structure so that the analytical modal properties agree with the modal properties estimated from the measured responses. Cha and de Pillis presents a model updating method which updates the analytical model of structure by using additional information obtained from the operation of adding known masses to the physical structure [3]. Bernal develops other damage detection method using Damage Locating Vectors (DLVs). This method first estimates modal properties by analyzing the measured responses and assembles the flexibility matrices at sensor locations from the estimated modal properties. DLVs are calculated from the singular value decomposition of flexibility matrix [1]. Nagayama et al. develop a structural identification method consisting of vibration modes identification and inverse analysis of structural properties from the identified modes. They apply the developed method to the ambient vibration measurements of a full-scale suspension bridge, determine the mode characteristics, and detect changes in the structural properties [16]. The accuracy of system identification depends on the arrangement of sensors. So the sensor deployment can be treated as an optimization problem. Kripakaran and Smith present approaches for design of initial sensor deployment and the iterative placement of sensors for model filtering and damage identification. This method first predicts the analytical responses of structural models with possible damage scenarios and then investigates the histogram of model predictions. The sensor deployment is determined so that the number of structural models effectively decreases [10]. Raich and Liszkai present a multi-objective optimization approach which minimizes the number of sensors while maximizing the sensitivity of the frequency response functions (FRFs) collected at each specified sensor location with respect to all possible damaged structural elements [19].

It is often criticized that the accurate structural model cannot be obtained for existing structures and also that the modal analysis is time consuming and expensive. Therefore, online measured response based method, that is, structural model-free method is studied. Posenato et al. present two statistical approaches of moving principal component analysis and moving correlation analysis to identify and localize anomalous behavior in civil infrastructure [18]. Sohn and Farrar present a damage diagnosis method in which measured acceleration time series are solely analyzed to find out the difference from the time series predicted using the closet AR-ARX model. The AR-ARX models are determined in advance from the acceleration responses of non-damaged structure measured under various environmental conditions. The increase in residual errors would be maximized at the sensors instrumented near the actual damage locations [21]. Fasel et al. investigate the applicability of a frequency domain ARX model to measured responses to detect non-linearity of damaged structure. It is shown that the vibration-based method is, while able to detect anomaly when damage is present in structure, is unable to localize the damage. They also investigate the applicability of a frequency domain ARX model to the data obtained from an impedance-based active sensing method [17] and show that their method is able to localize the damage [6].

The accuracy and spatial resolution of damage detection highly depends on the sensor deployment. WSN is expected to improve the accuracy and spatial resolution of damage detection because WSN decreases installation and maintenance cost of sensor networks and thus a large number of sensors can be deployed in a target structure [14]. One of the critical issues of WSN is how to decrease energy consumption of wireless sensor nodes. Lynch et al. present a power-efficient wireless structural monitoring system with local data processing. The developed wireless sensor node is able to measure time-history response using a Micro Electronic Mechanical Systems (MEMS) accelerometer and perform computational tasks associated with system identification and damage detection instead of transmitting the raw measured response to a central server. The computation on the sensor node results in the saving of electricity [13]. Smarsly and Law present an agent migrations approach for performing simple resource-efficient routines to continuously analyze, aggregate, and transmit the sensor data to a central server [20]. Reliable data transportation, compression of data size, and time-synchronization are also important features of WSN. Xu et al. develop a WSN system, called Wisden, for structural monitoring which implements the scheme achieving the above three features. In their system, a data time-stamping method is implemented to avoid global clock synchronization [22]. Kim et al. deploy 64 wireless sensor nodes on the Golden Gate Bridge, measure ambient vibration using MEMS accelerometers, and estimate FRFs and mode shapes. It is shown that the collected data agrees with theoretical models and previous studies of the bridge [9]. Kijewski-Correa et al. present a WSN system with multi-scale approach. In their system, once globally distributed wireless sensor nodes detect anomalies by analyzing the acceleration responses, the system measures strain responses using sub-networks in the vicinity of suspected damage location. The time series of acceleration and strain responses are described using an ARMA model. The damage is detected based on the residual error of the ARMA analysis [8].

The approaches mentioned above are mostly based on the analysis of ambient vibration. Since an artificial excitation is

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