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Model updating method for damage detection of building structures under ambient excitation using modal participation ratio

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ABSTRACT

This paper presents a model updating method for the damage detection of building structures on the basis of modal participation without the need for system identification to extract the modal parameters. The presented method uses the modal participation ratio (MPR), which is defined by a representative value of modal responses extracted from vibration responses measured by sensors mounted on a building structure, as an indicator of the extent of modal contribution. Such MPR extraction assumes that the structure is under ambient excitation; thus, no loading on the structure is required to apply the presented method. In the model updating method, the differences between MPRs extracted from the sensors and MPRs estimated from a model are established as objective functions that are generated corresponding to the number of modes considered. These functions are minimized by a multi-objective optimization algorithm while searching for the optimal properties of a dynamic system, and the finally derived optimal solution is regarded as a baseline model that reflects the actual behaviors of a structure. Through analyses of the variations of the MPRs based on the damage scenarios of the derived baseline model, specific rules for damage localization are derived. In addition, to identify the damage severity of a structure, a damage severity function that describes the relationship between damage severity and MPR variation based on the baseline model is proposed. The proposed method is employed to construct a baseline model and detect the location and severity of the damage of a multi-story structure under ambient excitation.

1. Introduction

A structural health monitoring (SHM) system has been developed based on advanced sensing technology to evaluate the state and ensure the safety of structures [1–4]. Such a system has also been applied to real structures [5–8]. SHM includes the process of examination, which measures structural responses, such as stress, displacement, and vibration, using sensors, and the process of diagnosis, which provides significant information about the health of a structure via data processing and analysis of the measured structural responses. The most useful and widely applied information about structural health is a modal parameter, such as natural frequency, mode shape, or modal damping ratio. These parameters are unique characteristics of a structure, and they can be extracted from measured vibration responses. The process of deriving such information is referred to as system identification (SI) [9–10]. When a structural system experiences abnormal conditions or undergoes a change in mass, stiffness, or structural damping, the values of the above-mentioned parameters change with a certain tendency. Thus, by using such modal parameters, the studies on the safety evaluation of structures have been actively conducted to develop damage identification methods based on model updating and machine learning techniques [11–14].

Previous studies on the damage detection of structures have increasingly employed artificial neural networks (ANNs) with modal parameters. In these studies, ANNs have been developed to identify the location and level of damage via training for recognition of the relationships between the unique characteristics and the system properties of a healthy structure and a damaged one [14]. Such ANN-based studies on damage detection have typically employed modal parameters extracted from a structure. Bakhary et al. [15] and Gonzalez and Zapico [16] proposed ANN models in which the modal parameters (natural frequency and mode shape) of a structure before and after damage were set as the inputs and the stiffness and mass were set as the outputs, and they adopted these models for damage detection of a one-story portal frame

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and a five-story building, respectively. Machavaram and Shankar [17] developed a time-domain damage detection technique in which the time histories of the measured acceleration responses were set as the inputs and the rotational stiffness of a structural member was set as the output in a radial basis function neural network without extracting the modal parameters. This technique was validated by a numerical study that employed dynamic responses extracted by applying impulse loading to healthy and damaged multi-story structures. Abdeljaber et al. [18] proposed a damage detection method to establish the relationship between the damage probability and the time history of the measured acceleration response for a structure under ambient excitation by using a convolutional neural network. This method was adopted in an experimental study for detecting the damage of a steel frame. In the experiment, the damage of the frame was implemented by loosening the beam joint of the frame; then, the location and degree of the damage were identified using the established neural network. The above-mentioned ANN-based damage detection studies have employed structural responses or modal parameters obtained from measurements as training data in the neural networks. In particular, as information on the damaged structures, the responses obtained from intentionally damaged specimens and simulation models that were assumed to be damaged were used to construct ANN architectures in these studies. However, from a practical point of view, in contrast to mass-produced small-scale mechanical structures, it is not easy to generate the structural responses or modal parameters of a civil or building structure in a damaged state that may exist in the future, which are required for training the ANN in the present. Furthermore, ANNs trained by information on damage localization or severity and structural responses obtained from damaged structures have not shown sufficient reliability in identifying current and future damages.

The finite element (FE) model updating method has been developed as an alternative for identifying structural damage. It uses vibration responses measured by sensors to construct a structural model that closely resembles the real structure. Model updating methods typically employ modal parameters extracted from the vibration data of structures measured before and after damage. In this method, an error function for the modal parameters between the measurement and the model is established and minimized while determining the system properties or locations as well as the extent of stiffness reduction. Finally, an FE model showing a similar behavior to a real structure is produced and used for damage identification as a baseline or damaged model [19–21].

As most model updating methods for damage detection employ modal parameters, the errors of modal parameter-related indicators between the measurement and the model are calculated for each mode in order to construct an objective function. Each mode has a different impact on the behaviors of a structure. Therefore, the formulation in the model updating process has allocated a different weight to each mode in order to construct an error function [22–24]. However, even though various methods have been proposed to consider the relatively different participations of each mode, no reasonable or reliable method for weighting each mode has been proposed thus far. Some studies [25–27] have employed the modal participation mass ratio (MPMR), which is presented in structural dynamics [28] to assess the modal contribution of each mode quantitatively, in the model updating process. In these studies, multiple candidate solutions are obtained by minimizing the constructed objective functions, which are as many as the modes considered. When a final solution is selected from these multiple solutions, the MPMR is applied as the weight value of the objective function for each mode. However, because the MPMR used in these methods is calculated based on the theory of structural dynamics and an analytical model that involves many assumptions and uncertainties, it may differ from the real MPMR value of the target structure.

As mentioned above, the SI process is required to extract a modal parameter, which is the most important element in the study of damage detection, from the measured vibration responses of a target structure. Many studies [6,29–31] have confirmed that the natural frequency and damping ratio vary with the amplitude of the excitation force and the environmental conditions around the target structure. Moreover, the extracted modal parameters vary with the type of applied SI technique as well as with the parameters employed in the SI methods [6]. In particular, field tests for large-scale civil and building structures include considerable uncertainties induced across the overall measurement process. Therefore, it is difficult to stably extract a modal parameter having a constant value.

Further, damage detection methods based on the time series of structural responses measured from a structure have been developed. These methods do not require the extraction of modal parameters because they directly employ vibration data measured in the time domain. Xu et al. [32] and Machavaram and Shankar [17] proposed ANN-based damage detection methods in which the measured dynamic displacement and acceleration responses are set as the inputs, respectively, and the stiffness of the structure is set as the output. As the measured time history data of the vibration responses are directly used, no modal parameter needs to be extracted from the target structure. These methods require the force information of sinusoidal excitation and impulse loading, respectively, for experimental validation. The method proposed by Li and Hao [33] predicts the location and degree of stiffness reduction in a structure by a model updating technique that minimizes the difference between the measured time history of dynamic responses and the reconstructed responses of a model without the extraction of modal parameters. This method requires load information to acquire the structural responses, and information on the impact force measured in the loading test for validation of the method is used in the model updating process. An and Ou [34] proposed a damage detection method based on model updating with multiple cost functions constructed from the measured vibration responses. Among these cost functions, two functions were obtained from the time history of acceleration responses measured during free vibration and used for damage detection. The method was validated using the free vibration response induced by an impact force acting on a truss bridge. In the above-mentioned methods, the time histories of structural responses were stably obtained from tests without the SI process and used for damage detection. However, these methods require loading tests and force information. A small-scale structure that can be loaded by a relatively simple method can accommodate such methods. However, for a large-scale civil or building structure, which involves a complex process and high excitation costs, the application of the above-mentioned methods may be difficult or even impossible.

In this study, a model updating method for damage detection by using structural responses measured from ambient vibration tests for the building structures is presented based on the modal participation. To consider the modal participation of the structure in the model updating process, a modal participation ratio (MPR) that denotes the representative value of the time history of the modal response obtained from the vibration response is defined and employed in the presented method. The MPR extracted for the modes under consideration acts as the main factor in the error function of the model updating and thus facilitates the construction of a baseline model that quantitatively reflects the modal characteristics of the target structure. In the model updating process, these error functions, which are set to be as many as the modes under consideration, are defined as the MPR differences