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Data fusion of acceleration and angular velocity for improved model updating

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ABSTRACT

In the traditional finite element (FE) model updating, translational responses, such as acceleration, have generally been employed to identify the structural properties. However, the boundary conditions of a structure are associated with both translational and rotational DOFs. Thus, the combinational measurement of translational and rotational responses (e.g., angular velocity) would increase accuracy of FE model updating of structures, especially in identifying their boundary conditions. This paper proposes data fusion of translational and rotational responses for improved system identification using FE model updating technique. In the proposed method, the accelerometers and gyroscopes are installed in between and near the supports of a structure, respectively, and FE model updating is carried out using the natural frequencies, the translational mode shapes obtained from accelerations, and the rotational mode shapes obtained from angular velocities. Numerical and experimental verifications are carried out on simply-supported beam structures. The verifications show that the proposed FE model updating strategy based on the data fusion results in more accurate assessment of both structural properties and boundary conditions than the traditional FE model updating using translational responses only.

1. Introduction

Civil engineering structures are exposed to various types of loadings, such as earthquakes, ocean waves, typhoons, and overloaded traffics. The loadings applied to a structure possibly bring structural deterioration or damage, which can lead to the failure of the structures. Given that the structural failure causes significant economic and social loss, most countries take care of the civil engineering structures using various maintenance approaches such as visual inspection, campaign and long-term monitoring, numerical simulation, and routine retrofit.

A finite element model is initially developed to provide an effective tool simulating behavior of large and complex structures whose properties are difficult to assess analytically. Accurate FE models can provide responses under extreme loading events or long-term environmental loadings, which helps to build the maintenance strategies [1–5]. Since 1990 s, the FE model has been used to provide a baseline to identify system parameters of structures inversely from input/output measurements [6–9]. Because the actual structure may be different from its design drawing due to the construction error, structural deterioration, and/or structural damage, parameters in the FE model determined by the design drawing would also be different from those of the actual structure. If measurements from the structure are available, the system parameters can be estimated by minimizing the difference between the FE model and the physical structure. The minimization process is called FE model updating.

In the FE model updating, acceleration responses are generally employed to determine modal properties (i.e., natural frequencies and mode shapes) of a structure, which are subsequently used to update the numerical model. The modal properties have input independency and unique correlation with the structural parameters (at least theoretically), and thus they are appropriate to identify the unique parameters of a structure by the minimization process. The identifiable system parameters are structural properties (i.e., material and geometrical properties) and boundary conditions. In many researches, however, the structural properties are only included in the updating parameters and the boundary conditions have not been considered in the FE model updating with presuming them as hinged, roller, or fixed [4,5,8–10]. In some cases where the boundary conditions are given uncertain, the boundary condition has been included in the updating parameters.

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For example, Aktan et al. [11] considered the boundary conditions of a numerical bridge for the manual FE model updating by implementing rotational springs at the supports. Sanayei et al. [12] introduced soil-substructure interaction model to assess the boundary conditions of a numerical bridge model using an iterative Gauss–Newton method. Catbas et al. [13] manually calibrated boundary conditions of the Commodore Barry Bridge before the iterative FE model updating process. In their example, all bearings were assumed as fixed due to the best agreement of two lower natural frequencies, and the appropriateness of the assumption was not investigated. Zhang et al. [14] updated the FE model of the Kap Shui Mun Cable-stayed Bridge, and the boundary conditions between the deck and piers, and the deck and towers were included in the FE model updating. The boundary conditions were changed up to 200% from the initial values by the FE model updating, and the accuracy could not be verified. Yi et al. [15] successfully updated the FE model of the Haengju Cable-stayed Bridge with the boundary condition as an updating parameter. The boundary condition was found to be partially restrained, which was indirectly verified by investigating the improvement of modal properties by the updating. The literatures used translational modal properties estimated numerically or from the acceleration measurements for the FE model updating.

In the literatures, the boundary conditions were commonly modeled using rotational springs at the boundaries. This modeling is substantial, since the types of boundary conditions, such as fixed, hinged/roller, and in between, is generally determined according to the resistance of the rotational moment. However, the literatures used the translational modal properties that were obtained numerically or identified from acceleration for the updating of system parameters including boundary conditions. The FE model updating identified the structural properties (i.e., the material and geometrical properties) of structures accurately, and the boundary conditions to some degree, possibly with the aid of natural frequencies sensitive to the boundary conditions. Nevertheless, limitation to the quantitative assessment of the rotational boundary condition still exists since the natural frequencies are directionless and easy to make the updating ill-positioned unless some accurate directional properties, such as mode shapes, are used together. For example, the decrement of the first natural frequency of a simply-supported beam may be from the degradation of its material, elongation of initially assumed span length, or loosening of its boundary conditions, and the exact cause of the decrement may not be distinguished without using mode shapes.

Therefore, higher accuracy can be achieved in the assessment of boundary conditions if rotational responses, such as inclination or angular velocity, are employed in the FE model updating. Recently, the advances in the sensor technology have enabled low-cost and high-precision gyroscopes that measures angular velocity based on the Coriolis Effect. The gyroscopes can provide rotational information of a structure which has high sensitivity to the boundary conditions. Since the translational measurement using acceleration is still attractive for identifying the structural properties, the combined use of accelerometers and gyroscopes are preferable for accurate assessment of both structural properties and boundary conditions. The combined use of multiple data to yield a consistent, accurate, and useful representation of an object is called the data fusion technology [16]. While the concept of data fusion is not new, the emergence of new sensors, advanced processing techniques, and improved processing hardware make real-time fusion of data increasingly possible [17,18]. In the civil engineering field, the advantage of the data fusion technology has been verified in the application to the damage detection [19,20] and the estimation of responses at the unmeasured locations [21].

In this paper, novel FE model updating strategy based on data fusion of acceleration and angular velocity has been proposed to assess the structural properties as well as the boundary conditions with high accuracy. Using accelerometers and gyroscopes, the accelerations in the translational DOF and angular velocities in the rotational DOF are collected on a structure together. The translational and rotational modal properties are obtained by the modal analysis, and constitute an objective function to be minimized. The proposed strategy has been verified using a simply-supported beam in the numerical simulation, and a real beam in the lab-scale experiment. The accuracy of the system parameters (i.e., structural properties and boundary conditions) identified by the proposed FE model updating strategy are compared with those identified by the conventional accelerometer-based FE model strategies for the verification. Consequently, the combined use of acceleration and angular velocity gives richer information than the sole use of acceleration, allowing the enhanced performance particularly in determining the boundary conditions.

2. FE model updating

2.1. Acceleration-based FE model updating

The FE model updating starts from building an objective function to minimize the differences between the modal properties from the initial FE model and from the measurement. The differences (i.e., residuals) are defined for the types of modal properties (e.g., natural frequencies and mode shapes) and the mode number. Möller and Friberg [22] tested various types of objective functions and reported the best objective function for large-scale FE model updating as

$$J = \sum_{i=1}^{N_m} (w_{1,i} J_{1,i} + w_{2,i} J_{2,i}) \tag{1}$$

where $J_{1,i}$ and $J_{2,i}$ are the normalized residual functions of natural frequencies and mode shapes (from translational DOF). They are defined as

$$J_{1,i} = \left(\frac{f_{EXP,i} - f_{FE,i}}{f_{EXP,i}} \right)^2 \tag{2}$$

$$J_{2,i} = \frac{(1 - \sqrt{\mathrm{MAC}_{t,i}})^2}{MAC_{t,i}} \tag{3}$$

where $f_{EXP,i}$ and $f_{FE,i}$ are the ith natural frequencies obtained from the experiment and the FE model, respectively; $\mathrm{MAC}_{t,i}$ are the modal assurance criterion (MAC) values between ith experimental mode shapes in the translational direction and the corresponding mode shapes from the FE model; N_m is the number of used modes; $w_{1,i}$ and $w_{2,i}$ are the weighting factors for residual functions of ith natural frequencies and translational mode shapes (i.e., $J_{1,i}$ and $J_{2,i}$).

2.2. Data fusion-based FE model updating

The improvement of the data fusion-based FE model updating from the acceleration-based updating is addition of a residual function for rotational mode shapes in the objective function in Eq. (1). Then the objective function can be modified as

$$J = \sum_{i=1}^{N_m} (w_{1,i} J_{1,i} + w_{2,i} J_{2,i} + w_{3,i} J_{3,i}) \tag{4}$$

$$J_{3,i} = \frac{(1 - \sqrt{\mathrm{MAC}_{r,i}})^2}{\mathrm{MAC}_{r,i}} \tag{5}$$

where $J_{3,i}$ is the normalized residual functions of rotational mode shapes; and $\mathrm{MAC}_{r,i}$ is the MAC value between ith experimental