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An improved wavelet–Galerkin method for dynamic response reconstruction and parameter identification of shear-type frames

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ABSTRACT

An improved wavelet–Galerkin (IWG) method based on the Daubechies wavelet is proposed for reconstructing the dynamic responses of shear structures. The proposed method flexibly manages wavelet resolution level according to excitation, thereby avoiding the weakness of the wavelet–Galerkin multiresolution analysis (WGMA) method in terms of resolution and the requirement of external excitation. IWG is implemented by this work in certain case studies, involving single- and n-degree-of-freedom frame structures subjected to a determined discrete excitation. Results demonstrate that IWG performs better than WGMA in terms of accuracy and computation efficiency. Furthermore, a new method for parameter identification based on IWG and an optimization algorithm are also developed for shear frame structures, and a simultaneous identification of structural parameters and excitation is implemented. Numerical results demonstrate that the proposed identification method is effective for shear frame structures.

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1. Introduction

Structural dynamic responses are often utilized to evaluate structural health condition in vibration-based damage assessment techniques. To achieve dynamic structural responses, the structural equation of motion should be solved. Conventionally, this equation is solved in three manners, i.e. frequency-domain [1,2],time-domain [3–5] and modal-domain methods [6–8]. The frequency-domain method is an effective and efficient scheme that uses fast Fourier transform algorithm (FFT) to calculate frequent-dependent structural responses and frequency response functions. However, although the FFT-based method can sufficiently describe the frequency-domain characteristics of response signals, it cannot provide any local time-domain information about them. In addition, this method cannot handle non-stationary signals [9]. Meanwhile, the time-domain method is an intuitive and accurate direct signal analysis scheme. However, similar to the frequency-domain method, this technique cannot provide any frequency-domain information about response signals. Additionally, the time-domain responses acquired using transducers are often weak signals that are susceptible to different noises. Thus, certain pre-processing procedures, such as amplification, filter and trend term elimination, are needed to improve the signal–noise ratio before the time-domain signals are utilized for structural damage identification [10]. Frequency- and time-domain methods are used to solve the structural equation of motion under the physical coordinate system. Finally, the modal-

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domain method is used to solve the structural equation of motion under the modal coordinate system by conversion of coordinates. When integrated with the substructure technique, this method analyses complex structural dynamics by focusing on the structural low-order modes because they dominate the dynamic response of structures. Thus, not all structural modes, including non-dominant high-order modes, have to be solved. Nevertheless, the modal analysis procedure therefore inevitably provides imprecise solutions for dynamic structural responses [11].

Wavelet analysis is an efficient signal processing measure that can be utilized to characterize a function that features compact support because it is used to voluntarily achieve the best compromise between frequency and time resolutions [12]. The representation of a wavelet basis produces a group of wavelet coefficients constituted on diverse levels of resolution. A coefficient is connected to a time-domain sample point and a resolution level. The coefficients connected to the low- and high-resolution levels describe the low- and high-frequency characteristics of signals, respectively [13]. These desirable features have attracted many researchers to resolving the structural equation of motion using wavelets [14–16]. The wavelet–Galerkin multiresolution analysis (WGMA) method is a ripe and effective procedure of solving the dynamic problems of structures [17–19]. However, the resolution of WGMA varies by problems, that is, it needs to be determined and compared by users to find the best values for specific conditions. For example, Lai et al. [19] provided preliminary conclusions for different resolutions in a shear structure case; however, these conclusions only apply to continuous external force. Furthermore, the resolution completely depends on the number of sampling points, which is generally constant in actual experiments.

Some studies have addressed parameter identification of structures where the procedure is based on a representation of the equations of motion according to wavelet [20–22]. These studies belong to the scope of wavelet multi-resolution and require complete structural responses, in which the resolution level needs to be determined appropriately. To alleviate the necessity of using dense sensors, researchers have studied parameter identification using part of structural responses [23–25]. Their work has improved the practicability of structural parameter identification. In addition, Wang and Yan [26] proposed a stiffness identification method for shear structures under an ambient excitation in which the natural excitation technique, the extended Kalman filter algorithm and a three-step method were synthetically utilized. Wang et al. [27] proposed a new proper orthogonal modes-based damage identification approach for shear-type buildings using singular-value decomposition and a particle swarm optimization (PSO) algorithm. Huang et al. [28] presented an efficient recursive least-squares estimation algorithm for identifying the time-varying structural parameters of a building structure under unknown excitations by assuming uniform shear stiffness when identifying structure parameters and excitation simultaneously. Luo et al. [29] proposed a damage index that uses the wavelet spectral transmissibility function and a constrained linear least squares method to locate and quantify the damage of a shear frame structure under non-stationary stochastic excitation. Zhang and Xu [30] recently developed a new damage identification technique using simultaneous reconstruction of response and excitation, where the Kalman filter and a radial basis function network were utilized.

An improved wavelet-Galerkin (IWG) method, which considers the defects of WGMA and focuses on resolution and excitation, is proposed for reconstructing structural responses. Then, the proposed method is applied in the simultaneous identification of parameter and excitation of shear frames with non-uniform stiffness subjected to a seismic excitation. In this study, only a few incomplete response measurements are integrated with an ordinary optimization method. The effectiveness of the proposed method is illustrated through several cases.

2. Improved wavelet-Galerkin (IWG) method

2.1. Structural dynamic equation

The dynamic responses of a single-degree-of-freedom (SDOF) shear-frame structure are shown in Fig. 1. The corresponding dynamic equation is

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t) \tag{1}$$

where M, C, K are the mass, damping and stiffness respectively, and $F(t), x(t)$ are the external force and the displacement of the structure, respectively.

For an n- degree-of-freedom (nDOF) shear-frame structure, the equation of motion is

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \boldsymbol{C}\dot{x}(t) + \boldsymbol{K}\boldsymbol{x}(t) = \boldsymbol{F}(t) \tag{2}$$

where $\boldsymbol{M}, \boldsymbol{C}, \boldsymbol{K}$ are the mass, damping, and stiffness matrices respectively, and $\boldsymbol{F}(t), \boldsymbol{x}(t)$ are the force and displacement vectors, respectively. The equation is decoupled with the principle of mode superposition by substituting $\boldsymbol{x} = \sum_{i=1}^{nd} \eta_i X^i$ into Eq. (2). Both left-hand sides are then multiplied by X^{jT}. For orthogonality, Eq. (2) is simplified as

$$M_j^* \ddot{\eta}_j + C_j^* \dot{\eta}_j + K_j^* \eta_j = X^{jT} \boldsymbol{F}(t) \quad (j = 1, 2, 3......nd) \tag{3}$$

where η_j, X^j, X^{jT} are the jth mode-coordinate, mode and transposed mode respectively, and $M_j^* = X^{jT}\boldsymbol{M}X^j$, $C_j^* = X^{jT}\boldsymbol{C}X^j$, $K_j^* = X^{jT}\boldsymbol{K}X^j$, which are the generalized mass, damping and stiffness respectively. Eq. (3) is the n-decoupled equation of Eq.

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