ARTICLE IN PRESS

Measurement xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Improved decentralized structural identification with output-only measurements

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ARTICLE INFO

Keywords:
Decentralized structural identification
Damage identification
Model updating
Force identification
Vibration measurements
Nonlinear system

ABSTRACT

This paper proposes an improved decentralized structural identification approach with output-only measurements. The improved approach can be used for system identification of both linear and nonlinear structures. A large-scale structure is divided into a number of smaller zones according to its finite element configuration. Each zone is dynamically tested in sequence with its own set of sensor placement. The external excitation forces in each zone are identified using the Kalman filter technique. Structural parameters of the whole structure are divided into several subsets and then updated by using the Newton-SOR method. Both the external excitations and structural parameters are iteratively updated until a defined convergence criterion is met. The proposed technique is then applied to two numerical examples: a six floor building and a planar truss structure. The nonlinear system parameters of the building are correctly identified. The unknown excitation force, damage location, and damage severity in the plane truss structure are successfully identified. The effect of measurement noise on the identified results is also studied. An eight floor shear type structure is finally tested in the laboratory. The experimental results further verify the effectiveness and efficiency of the proposed technique in damage identification using output-only measurements.

1. Introduction

Numerous efforts have been made to develop structural identification methods with unknown input to satisfy the general practical application requirement in field because the input excitation is difficult to be measured under operational conditions of civil structures. When only the output structural responses are available, the corresponding methodologies are usually referred to as output only techniques. Most techniques of this kind identify both the structural parameters and excitation forces simultaneously or successively via an iterative manner. Li and Chen [1] proposed a statistical algorithm to identify the structural parameters and the input information sequentially. Lu and Law [2] proposed a two-stage method based on the dynamic response sensitivity to identify both the structural parameters and excitation forces. Other methods based on Quadratic Sum-Squares Error [3], Sequential nonlinear least-square estimation [4], Extended Kalman Filter [5], etc. have also been reported to conduct the damage identification with unknown input.

Many structural identification techniques are based on the assumption that the structure behaves linearly [6–8]. However, structural failures or damage generally cause nonlinearity to some extent, and therefore damage detection for structures with nonlinear behavior should be considered. Kalman filter technique is one of the most promising methods for nonlinear structural identification. Lei et al. [6] proposed a Kalman filter technique for the identification of nonlinear restoring force with limited input and output measurements. The algorithm sequentially applied the classical Kalman estimator for estimating the structural responses and the recursive least squares estimation for identifying the nonlinear restoring force and unmeasured excitations. Wu and Smyth [7] proposed a damage detection method based on unscented Kalman filter to identify the hysteretic differential models with degradation and pinching. Xie and Feng [8] proposed an iterative unscented Kalman filter for nonlinear structural identification.

The conventional system identification and damage detection methods at the structural element level may be well suitable for small to medium-size structures, but not necessarily suitable for large-scale structures with a large number of structural parameters because a large amount of data is required. In addition, the system identification is generally an inverse problem, which needs a number of iterations and is computationally intensive. The capital cost for sensor installation, practical problems associated with power supply, and the data processing capability of hardware are several typical adverse factors for a

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http://dx.doi.org/10.1016/j.measurement.2017.09.029
Received 10 July 2017; Received in revised form 19 August 2017; Accepted 18 September 2017

Please cite this article as: Ni, P., Measurement (2017), http://dx.doi.org/10.1016/j.measurement.2017.09.029

high density sensor configuration. Therefore efficient damage detection and model updating with less numbers of sensors is of emerging interest.

Substructural analysis and identification approaches have been proved to be effective and efficient for large scale structures. Weng et al. [9] proposed an inverse substructure-based finite element model updating technique in the frequency domain. The modal data measured on the global structure are disassembled to substructural flexibility matrices, under the force and displacement compatibility constraints. The substructural eigenparameters can be used to identify local damages, which are more sensitive than the global eigenparameters [10]. Several researchers have developed substructure-based system identification techniques in the time domain. Koh et al. [11] proposed a "divide-and-conquer" damage detection method and the substructural parameters were identified using a genetic algorithm. Yuen and Katafygiotis [12] proposed a substructural identification method based on Bayesian inference. The method calculated the probability distribution of the parameters for identification. Not only the best estimates of the parameters but also their uncertainties can be qualified. Law et al. [13] performed structural damage detection from coupling forces between substructures. Lei et al. [14] proposed a substructural identification method based on the extended Kalman filter. The large-scale structure is divided into several small substructures, and the interface effect from adjacent substructures is treated as unknown input forces. The interface forces of each substructure are identified using the extended Kalman estimator and least-squares estimation.

Time domain substructural identification methods usually have two limitations: (1) the measurements of the interface forces should be available; and (2) the number of sensors should be equal to or larger than the number of interface forces. Several methods have been developed to deal with the first limitation. Koh et al. [15] eliminated the requirement of interface forces using different sets of measurements of the substructure under the same dynamic excitation and thus the interface measurement was not necessary. Li and Law [16] proposed a wavelet based transmissibility matrix for substructural damage identification, where the dynamic responses at one set of degrees-of-freedom (DOFs) of the target substructure were reconstructed from another set of measurement responses. The local damages were identified from minimizing the differences between the measured and the reconstructed sets of responses. Consequently the interface measurements are not required. However, this method is still subject to the second limitation, that is, it requires the number of sensors to be equal to or larger than the number of interface forces [17].

The decentralized method is an alternative solution to the large-scale system identification, which shares the similar idea "divide-and-conquer" of the above-mentioned substructural approaches. Decentralized methods have a significant advantage when used for the full scale model updating. It could conquer the abovementioned two limitations that the substructural methods may suffer from, to have a good estimation of the pseudo-inverse in the identification by formulating the global optimization as a set of smaller size optimization problems. Decentralized methods have been used for modal identification. Sim et al. [18] proposed a decentralized modal analysis using a decentralized topology in smart wireless sensor networks. The proposed approach consisted of two main steps: the first is the local feature extraction using Eigensystem Realization Algorithm (ERA) or Natural Excitation Technique (NExT) and the other is the global modal property determination using the aggregated local properties in the base station. Another decentralized modal identification method was proposed by Jo et al. [19]. This method was embedded into Imote2 wireless sensor platforms for wireless structural health monitoring. The efficiency of the decentralized modal identification using high-sensitivity sensors was experimentally verified using a steel truss structure. Decentralized methods were also proposed for structural damage identification. Wu et al. [20] proposed a parametric damage detection method based on neural networks. Yun et al. [21] proposed a decentralized damage identification method based on wavelet signal analysis tools. The discrete wavelet coefficients of acceleration were used for damage identification with wavelet entropy indices.

This paper proposes an improved decentralized structural identification technique for both linear and nonlinear structures, by extending the authors' pervious work [22] on damage identification of linear structures only. The significant improvement to further develop the decentralized approach for nonlinear structural identification in this study. The proposed approach combines the Kalman filter technique for force identification and the Newton-SOR method for damage identification. It owns the advantages of both the decentralized method and Kalman filter technique, and could be used for both linear and nonlinear structural identification. The basic formulations of the improved decentralized structural identification approach are described in Section 2. In Section 3, numerical simulations and identification results obtained from a nonlinear system and a planar truss structure are presented and discussed. Experimental studies on an eight-floor building structure are presented in Section 4, followed by the concluding remarks in Section 5.

2. Theoretical development

Extended and unscented Kalman filter based methods are promising for nonlinear system identification and have been intensively studied [5–8]. In the extended Kalman filter technique, both unknown structural parameters and forces are included in the state vector and a large number of unknowns may cause the state space equation unstable. Therefore, the method is only applicable to the system identification of small-scale structures with several unknown parameters. In the present study, the Kalman filter technique is used for the state estimation only and the unknown input forces are identified from the state vector with the optimization method. Since the unknown structural parameters are not included in the state vector, the dimension of the state vector is not large and the force identification can then be achieved even for large scale structures. A sensitivity based method, i.e. Netwon-SOR method, is adopted for the decentralized structural damage identification. The Tikhonov regularization is employed to solve the ill-posed inverse problem and obtain a stable solution.

2.1. Equation of motion of a linear or nonlinear system

The equation of motion of a structure under the external excitation can be written as

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \boldsymbol{F}_c(\dot{\boldsymbol{x}}(t)) + \boldsymbol{F}_s(\boldsymbol{x}(t),\ \theta) = \boldsymbol{B}\boldsymbol{f}(t) \tag{1}$$

where $\boldsymbol{M}$ is the $n \times n$ mass matrix, $\boldsymbol{x}(t) = [x_1(t), x_2(t), \cdots, x_n(t)]^{\mathrm{T}}$ is the displacement vector, $\boldsymbol{F}_c(\dot{\boldsymbol{x}}(t))$, $\boldsymbol{F}_s(\dot{\boldsymbol{x}}(t), \theta)$ and $\boldsymbol{f}(t)$ are the dissipating force vector, the stiffness force vector and the excitation force vector, respectively; $\boldsymbol{B}$ is the mapping matrix relating with the location of the applied forces, and $\theta = [\alpha_1, \alpha_2, \cdots, \alpha_{ne}]^{\mathrm{T}}$ is the unknown parameter vector of the structure with the number of elements as ne. It should be noted that the structural system could be linear or nonlinear, depending on the definition of the dissipating and stiffness force vectors.

The state vector is defined as

$$\boldsymbol{X}(t) = \begin{bmatrix} \boldsymbol{x}(t) \\ \dot{\boldsymbol{x}}(t) \end{bmatrix} \tag{2}$$

Transforming the equation of motion in Eq. (1) as a state equation, we have

$$\dot{\boldsymbol{X}}(t) = \boldsymbol{J}(\boldsymbol{X}(t), \theta, \boldsymbol{f}(t)) = \begin{bmatrix} \dot{\boldsymbol{x}}(t) \\ \boldsymbol{M}^{-1}\{\boldsymbol{B}\boldsymbol{f}(t) - \boldsymbol{F}_c(\dot{\boldsymbol{x}}(t)) - \boldsymbol{F}_s(\boldsymbol{x}(t),\ \theta)\} \end{bmatrix} \tag{3}$$

Usually, only a limited number of accelerometers are deployed on structures to measure the vibrational acceleration responses. The measurement vector can be written as