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Structural damage detection with limited input and output measurement signals

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ABSTRACT

It is important but still challenging to detect structural damage with limited input and output measurement signals. In this paper, an algorithm is proposed for detecting structural damage with limited input and output measurement signals. The algorithm is based on sequential application of an extended Kalman estimator for the extended state vector of a structure and least-squares estimation of its unknown external excitations. Analytical recursive solutions for the identification of structural parameters and unknown excitations are derived. Such straightforward derivation and analytical solutions are not available in the previous literature. Structural damage can be detected from the degradation of the identified element stiffness. Numerical examples of detecting damage of some small size structural systems are used to demonstrate the performances of the proposed algorithm. Then, the algorithm is extended to detect structural damage of large size structural systems based on substructure approach. Inter-connection effect between adjacent substructures is considered by 'additional unknown inputs' to substructures. It is shown that the 'additional unknown inputs' can be estimated by the algorithm without the measurements of the substructure interface DOFs, which is superior to previous identification approaches. A numerical example of detecting structural damage of a large size truss illustrates the efficiency of the proposed algorithm.

1. Introduction

Detecting structural damage or fault is an important but still challenging task because damage/fault is an intrinsically local phenomenon. Various structural damage/fault detection techniques have been proposed. Among them, approaches based on system identification (SI) have received great attention [1–6]. Identification of modal parameters of structural systems is important, but these global properties can hardly be used for the detection of local damage/fault in systems [1–4]. It is straightforward to identify structural damage based on tracking the changes of the identified values of structural parameters at the element level, e.g., the degrading of element stiffness parameters. However, as an inverse problem, damage detection by the conventional SI approach is challenging [5–7]. In practice, it is often impossible to deploy so many sensors that accurately measure all excitation inputs and response outputs of systems. It is highly

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desirable to deploy as few sensors as possible, so it is essential to explore efficient algorithms that can detect structural damage utilizing only a limited number of measured responses of structures subject to some unknown (unmeasured) excitation inputs.

The extended Kalman filter (EKF) has been studied and shown to be useful for structural identification with limited response outputs [8–11]; however, the traditional EKF approaches require that all excitation inputs are measured or available. Recently, Yang et al. [12] proposed an extended Kalman filter with unknown excitation inputs, referred to as EKF-UI, for the identification of structural parameters as well as the unmeasured excitation inputs. But the analytical recursive solutions by the EKF-UI are obtained by rather complex mathematical derivations. Recursive solutions for structural parameters and unknown excitation are derived simultaneously.

Identification of structural parameters without excitation information has also been explored by some researchers [13–19]. However, in these approaches, information about structural displacement and velocity response signals are assumed to be available or they are obtained through integration of measured acceleration responses. In practice, dynamic responses are normally measured by accelerometers. Error is incurred in obtaining velocity and displacement signals by integration. Hence, direct use of acceleration response signals is preferred over velocity and displacement signals.

Identification of a large number of unknown parameters in large size structural systems is more difficult due to ill-condition and computation convergence problems [7]. In addition, as the size of a structural system increases, its computational efforts increase tremendously [20]. Consequently, some substructural identification approaches have been proposed, in which a large size structure is decomposed into smaller size substructures with fewer DOFs and unknown parameters [7,21–22]. Interaction between adjacent substructures is accounted for by inter-connection forces at the interfaces between adjacent substructures [23–26]. However, previous substructural identification approaches require that measurements of all response signals at the substructure interface DOFs are available. Although the aforementioned EKF-UI approach [13] can identify the unmeasured excitation inputs to the structure, it still requires the deployment of sensors to measure all responses at the substructure interface DOFs for the identification of the inter-connection forces because the EKF-UI is based on the Kalman filter approach [12]. In practice, it is often impossible to measure all responses at the interface DOFs between substructures, e.g., it is very difficult to measure the rotational DOFs at the substructure interfaces.

In this paper, an algorithm is proposed for detecting structural damage with limited excitation input and response output measurements. The proposed algorithm is based on the sequential application of an extended Kalman estimator [27,28] for the recursive solution of the extended state vector of a structure and least-squares estimation of its unknown excitation inputs, i.e., recursive solution for extended state vector is initially estimated followed by the estimation of the unknown excitation via least-squares estimation. In the previous work such as EKF-UI [12], recursive solutions for structural parameters and unknown excitation are derived simultaneously. It is necessary to initially estimate the unknown excitation in order to estimate the extended state vector. Therefore, the proposed algorithm can identify structural parameters and unknown excitation in a sequential manner, which simplifies the identification problem compared with other existing work such as the EKF-UI.

It is also shown that the recursive solution by the EKF-UI can also be derived by sequential application of an extended Kalman filter for the extended state vector of a structure and least-squares estimation of its unknown excitation inputs, so the proposed derivation is more straightforward than that by the EKF-UI. Structural damage is detected from the changes of structural parameters at the element level, such as the degradation of identified element stiffness parameters. Numerical simulation examples of detecting structural damage of some small size structural systems are used to demonstrate the performances of proposed algorithm. These examples include the Phase I benchmark building established by the American Society of Civil Engineers (ASCE) for structural health monitoring [29,30], a plan truss, and a simply supported beam in finite element model.

Then, the proposed algorithm is extended to detect structural damage of large size structural systems based on the substructure approach. Due to the superiority of the extended Kalman estimator, i.e., recursive solutions for the extended state vector of each substructure are initially obtained followed by the estimation of unknown excitation values; the 'additional unknown inputs' to each substructure can be estimated based on the formulation of 'additional unknown inputs' without the measurement signals at the substructure interface DOFs. By comparisons, unknown excitations are initially estimated followed by the recursive solution for the extended state vector in the former EKF-UI approach. It is necessary to measure all the responses at the substructure interfaces DOFs. Thus, the proposed algorithm has superiorities over other existing substructural identification approaches in the identification and damage detection of large size structural systems [19–22,25]. A numerical example of detecting structural damage of a large size truss is studied to illustrate the efficiency of the proposed algorithm.

2. Structural damage detection of small size structural systems with limited input and output measurement signals

Based on the finite element model, the equation of motion of a small size linear structural system under unknown external excitation can be written as

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t)+\boldsymbol{C}\dot{\boldsymbol{x}}(t)+\boldsymbol{K}\boldsymbol{x}(t)=\boldsymbol{B}\boldsymbol{f}(t)+\boldsymbol{B}^{u}\boldsymbol{f}^{u}(t) \tag{1}$$

in which $\boldsymbol{x}(t)$, $\dot{\boldsymbol{x}}(t)$ and $\ddot{\boldsymbol{x}}(t)$ are vectors of displacement, velocity and acceleration response, respectively; $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are the mass, damping and stiffness matrices, respectively; $\boldsymbol{f}(t)$ is a measured external excitation vector; $\boldsymbol{f}^{u}(t)$ is an unmeasured