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A dynamic load estimation method for nonlinear structures with unscented Kalman filter

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ABSTRACT

A force estimation method is proposed for hysteretic nonlinear structures. The equation of motion for the nonlinear structure is represented in state space and the state variable is augmented by the unknown the time history of external force. Unscented Kalman filter (UKF) is improved for the force identification in state space considering the ill-condition characteristic in the computation of square roots for the covariance matrix. The proposed method is firstly validated by a numerical simulation study of a 3-storey nonlinear hysteretic frame excited by periodic force. Each storey is supposed to follow a nonlinear hysteretic model. The external force is identified and the measurement noise is considered in this case. Then a case of a seismically isolated building subjected to earthquake excitation and impact force is studied. The isolation layer performs nonlinearly during the earthquake excitation. Impact force between the seismically isolated structure and the retaining wall is estimated with the proposed method. Uncertainties such as measurement noise, model error in storey stiffness and unexpected environmental disturbances are considered. A real-time substructure testing of an isolated structure is conducted to verify the proposed method. In the experimental study, the linear main structure is taken as numerical substructure while the one of the isolations with additional mass is taken as the nonlinear physical substructure. The force applied by the actuator on the physical substructure is identified and compared with the measured value from the force transducer. The method proposed in this paper is also validated by shaking table test of a seismically isolated steel frame. The acceleration of the ground motion as the unknowns is identified by the proposed method. Results from both numerical simulation and experimental studies indicate that the UKF based force identification method can be used to identify external excitations effectively for the nonlinear structure with accurate results even with measurement noise, model error and environmental disturbances.

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1. Introduction

The exact information of external force of structures can contribute to structural system identification, condition assessment and maintenance. As a kind of inverse problem of structural dynamics, the force estimation is also an optimization process. In this process, the calculated structural response based on identified force is expected to be close enough to the

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measured response. Although advanced force transducers have been developed recently, the direct measurement of all the external force for structure will be infeasible due to the limited number of sensors required in engineering and lack of access to the position of the loads. Structures may perform nonlinearly during severe external excitation such as the excitations related to earthquake or strong wind [1,2]. Although the parameter identification is very important to the structural system it is difficult to initialize the parameter identification without the information of external force for nonlinear structures. The force estimation of nonlinear structural system would contribute effectively to the parameter identification. In other words, the accurate identification of the external force is one efficient way and first step to the system identification for nonlinear system. For the target nonlinear structures in this study with isolations or other energy dissipation components the main structure may have very few degrades in strength and stiffness during the moderate or even the severe earthquake but the exact knowledge of external excitation related to the earthquake definitely contribute to the methodology of the seismic design. Therefore, the proper external force identification methods for these kinds of nonlinear structures are of great importance in this condition. Currently, the investigations of dynamic load identification for linear structures is increasingly carried out while the identification of external force for nonlinear structure is still a difficult task due to the nonlinearity, model error and measurement noise.

A lot of force estimation methods have been developed and extensive reviews of structural external force identification are provided [3–6]. The external excitation estimation methods can be classified into two categories of frequency domain methods and time domain methods. Frequency response function (FRF) as a powerful tool in frequency domain generally used in structural identification has also been applied to force estimation based on the inverse Fourier transformation [7]. Time domain methods are actively investigated currently as alternative tools for the force identification. Time history response can also be directly used as the measured information and the objective of the optimization process is to minimize the error between the measured and the predicted structural response with the time domain method. Examples of vehicle-bridge interaction force, wind load and white noise excitation are concerned in the external force estimation [8–10]. This process can be formulated in state space and the time history of external force to be identified can be taken as unknowns. Regularization methods or some other optimization methods could be used to solve the state vector [11–14]. These methods in time domain are usually based on the finite element model of the structure which is often inaccurate due to the uncertainties in the property of structural material which affect the accuracy of inverse analysis [15]. Majority of the methods mentioned above consider the measurement noise but take the model of the structure as deterministic although some methods may be robust to the model errors [16].

The measurement noise and model error as stochastic process has been considered by state variable estimation in state space with Kalman filter [17]. Kalman filters have been applied in the state variable estimation and the external excitation estimation can be a separate process with recursive identification methods [18,19]. A large number of measurements are required and the separate identification process from the state space may cause the biased errors in the identification results based on the method mentioned above. Kalman filter as an effective tool for the online estimation has also been modified with a new state variable augmented by the discrete time history of the external force. The external force and the structural response, including displacement and velocity, are taken as the unknowns to be identified [20–23]. The measurements on structure may be limited but they can be re-constructed with the measured information and then be used for the load identification [20,24]. With the augmented Kalman filter, the force can be estimated on-line accurately. However, only a fraction of the system input identification methods was concerned with the force identification for nonlinear structural systems, which commonly exist in earthquake excitation [1].

More recently, methods of structural model updating and structural identification for nonlinear structures have also been developed with the extended Kalman filter. The extended Kalman filter is an effective means of parameter identification and external force estimation for the nonlinear structures and good results have been obtained [25–27]. It has been demonstrated that the identification based on EKF is effective for linear structures or structures with slight nonlinear property. Compared with EKF, the unscented Kalman filter (UKF) is an algorithm with higher accuracy for the nonlinear system identification [28–30]. In the identification process with UKF, the computation of Jacobin matrix is not necessary. UKF is more suitable to force identification of the civil structures with seismic energy dissipation component which performs with a strong nonlinear property during the severe external excitation such as earthquake, blast and strong wind [28–30]. The Monte Carlo methods including particle filters [1] and other ensemble Kalman filter can solve the inverse problem for the nonlinear systems with non-Gaussian posterior probability of the state [29,30]. These Monte Carlo methods can approximate the posterior probability of the state through the generation of a large number of samples. However, the Monte Carlo methods require a large number of samples, depending on the number of the factors in the state variable, making the identification process time consuming [29,30]. Until now, very few literature reports on the force identification methods with augmented state variable of force time history solved by UKF previously.

As shown in Refs. [10,16,31] the external force estimation methods have been developed with orthogonal decomposition, regularization or least-square method in two-step identification procedure. This study will develop a new force identification method for nonlinear structure based on an improved UKF estimation tool to reduce the number of unknowns with the augmented state variable and efficient computation. This method is formulated recursively in state space with the augmented state variable by the discrete unknowns in the time history of external force. In this study it is supposed that the force identification is preceded by a system identification step. Therefore, the parameters of the structural system are assumed to be deterministically known constants. The position of the external excitation is also assumed to be determined while the time history is identified with the proposed method. A hysteretic nonlinear frame is firstly studied numerically with a single exci-

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