

論文の内容の要旨

論文題目 Structural system evaluation under seismic excitation
 using adaptive Kalman filter
 (適応カルマンフィルターを用いた地震動下の構造システム評価)

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Structure system estimation is of great importance for earthquake-prone countries. The lack of information about integrities of structure after an earthquake may conceal potential safety hazards and largely delay re-utilization of infrastructure, which may cause financial and life losses. The structure system estimation mainly includes two parts. One is structural parameter identification and the other is system response estimation. Once structural parameters, which reflect damage conditions, are estimated, corresponding measures can be taken to prevent structural failures or undesired structural responses in the subsequent earthquakes or operations. System responses, especially displacements, can also be used to evaluate structural conditions. For example, the inter-story drift ratio (IDR), defined as inter-story drift normalized by story height, is a key engineering parameter of building damage assessment. Additionally, displacement of a non-linear system under strong earthquake is important because hysteresis information can be assessed.

Structural Health Monitoring (SHM) based on vibration measurement progressed rapidly in the past decade. While most SHM methods based on modal analysis assume linear behaviors of structures, making the application to structure with hysteresis responses difficult, SHM based on data assimilation methods, e.g. Kalman filter (KF), Extended Kalman filter (EKF), Unscented Kalman filter (UKF) and particle filter (PF), capable of handling non-linear behaviors, have recently been developed. Generally, a reasonable system model is firstly assumed; unknown system parameters are then augmented in the state vector; the state vector can be estimated in a recursive manner in time domain using both the model and measured responses in a stochastic manner. In this way, the unknown physical parameters, as well as unmeasured system responses,

can be estimated at the same time.

One of difficulties in this approach is that poor selection of noise characteristics in KF can lead to poor performance of the filter or even to divergence. There are two kinds of noise characteristics, i.e. process noise \mathbf{Q} and measurement noise \mathbf{R} , which represent the error of the assumed system model and error of measured signals, respectively. While measurement noise \mathbf{R} might be decided based on sensor characteristics, the process noise \mathbf{Q} requires a time-consuming and subjective trial-and-error tuning. Adaptive Kalman filters proposed to address these issues are so far applied only to a simple problem of parameter estimation of a single-degree-of-freedom (SDOF) system with known input excitation. In order to make the data assimilation method practical, automatic adaption of \mathbf{Q} should be investigated in more realistic problems.

First, parameter identification under known seismic excitation is studied with the extension to multi-degrees-of-freedom systems. An adaptive EKF with two computation modes are studied. The Robbins-Monro (RM) algorithm is combined with the EKF to adjust the process noise automatically. Two computation modes, corresponding to time-invariant (stable mode) and time-variant parameter identification (track mode), are employed in the extended Kalman filter-Robbins Monro (EKF-RM) method. The track mode is direct implementation of RM algorithm with EKF. The stable mode sets the \mathbf{Q} components corresponding to parameters zero while other components are set adaptively; the stable mode can thus handle systems which slowly change over time while the track mode can handle more general time-variant systems. The EKF-RM method is firstly numerically investigated with three simplified models, including a SDOF model, a 4-DOF lumped mass model and a 2D cable stayed bridge model. The ability of tracking parameter variation with the method is studied based on the 4-DOF lumped mass model as well. The EKF-RM method achieves accurate time-invariant parameter identification using stable mode and track stiffness variation instantaneously using track mode. The selection of the computation mode is decided by estimated velocity response. If large discrepancy exists between the estimated and real velocity, the track mode is used, otherwise stable mode is recommended. Additionally, the influence of the use of simplified models rather than accurate models in filter is studied based on a 3D four story frame model and a 3D cable stayed bridge model numerically. The system models in KF play an important role. An inappropriate system model can result in inconsistent parameter estimates under different earthquake excitations. Furthermore, the EKF-RM method is validated by three shaking table experiments from E-defense database, including a full scale bridge pier experiment, a full scale four story building experiment and a substructure experiment. Time-invariant system parameters are identified using the bridge pier and four story building experiment. Modal frequencies computed by identified parameters show good agreement with those obtained from modal analysis. Also, the

forward simulation using the identified parameters can reproduce the responses accurately. Time-variant parameter identification is then demonstrated by using the substructure experiment. The identified time-variant stiffness is consistent with measured hysteresis loops.

Subsequently, an EKF based displacement estimation method for nonlinear SDOF systems under seismic excitation is proposed. In this method, time interval with or without significant nonlinearity is firstly determined using the track mode of EKF-RM method. It is assumed that residual displacement is measured as static deformation after an earthquake. For the time interval of linear behavior, i.e. initial and ending parts of the time history, the observations are acceleration and displacement, which is the summation of double-integrated displacement with high-pass filtering and residual displacement. Regarding the time interval with strong nonlinearity, two EKF schemes are proposed, i.e. one using an augmented state vector with time-variant stiffness parameter estimation and the other assuming a bi-linear system model with optimized model parameters. For both schemes, the incremental Newmark-beta method is employed in the prediction step of EKF. The results are further smoothed by extended Kalman smoother (EKS). The proposed method is numerically verified with SDOF system of three hysteresis models, including bi-linear, tri-linear and Bouc-Wen model. The performance is studied under four different earthquakes of two amplitude levels. Furthermore, the proposed method is validated by shaking table experiments from E-defense database, i.e. a full scale bridge pier experiment and a full scale four story building experiment. The estimated displacements using the proposed method present good accuracies for both the numerical and experimental investigations.

Lastly, parameter identification under unknown seismic excitation is studied. Conventionally, KF based estimation methods require that measurements of seismic excitations be available. However, there are cases where input excitations are difficult or impossible to obtain. Therefore, a state vector including not only system response and parameter variables but also input is employed in the EKF method to solve the joint-state-parameter estimation problem. An offline noise estimation method is combined with the EKF method to adjust process noise covariance matrix \mathbf{Q} automatically. The adaptive EKF-UI (unknown input) method is firstly presented as well as some criteria about joint state-parameter-input estimation problem. Subsequently, the proposed method is numerically investigated with two simplified models of a bridge pier and a 2D four story frame structure. Additionally, the adaptive EKF-UI method is combined with a substructure method and studied on the bridge pier model and a 3D cable stayed bridge model numerically. Furthermore, the proposed method is validated by two shaking table experiments from E-defense database, i.e. a full scale bridge pier experiment and a full scale four story building experiment. System parameter identification results show agreement with those obtained considering known inputs condition. The estimated seismic excitation signals coincide

with the measured ones well. Forward simulation using the identified parameters is shown to reproduce the structural responses.

The study in the thesis addresses problems in the application of filtering methods in structural system evaluation using seismic response data. The filtering methods had been limited to ideal numerical simulations and oversimplified experiments. This study improves the numerical stability and accuracy in the inverse problem and achieves parameter estimation and displacement estimation under realistic conditions. However, because of the complexity of some structures and their responses, the proposed methods are expected to be further improved for their wide-spread use in post-earthquake assessment of a variety of structures.