論 文 の 内 容 の 要 旨

論文題目　Stiffness condition assessment of bridge lateral resisting systems with unscented Kalman filter using seismic acceleration response measurements
（地震応答計測を利用したアンセンテッドカルマンフィルタによる橋梁の水平方向復元力特性同定）

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Stiffness assessment of bridges under seismic excitation is of great importance especially in earthquake-prone countries. The identification reveals dynamic characteristics and allows condition assessment. Seismic response measurements from small and frequent earthquakes (e.g. aftershocks) and analysis of these records may reveal deficiencies in stiffness which may be due to large main shocks or poor construction quality. If condition is assessed, corresponding measures can be taken to prevent failure/undesired response during future big earthquakes. Using seismic response measurements from large earthquakes, both residual stiffness and hysteresis response can be theoretically identified, which would provide substantial information on the behavior of the element. Hysteresis response can provide the total energy dissipation of the element and hence enable the engineer to assess occurred damage. Decisions towards closure or repair may be made more rapidly in the aftermath. However, ground motion and response records of bridges during earthquakes are often not available, except for some signature bridges; even if data is available, the identification techniques have limitations.

Current structural identification methods have several problems in terms of application to real bridges. These methods can be grouped in two general categories, namely, a) Frequency Domain Methods and b) Time Domain Methods. While the frequency domain methods provide modal parameters, the conversion from the modal to the physical domain is difficult as the conversion usually requires empirical knowledge. In addition, most modal identification methods assume linear behaviors of structures; the structural performance including the nonlinear characteristics, such as hysteresis responses, is difficult to evaluate. On the other hand, typical time domain methods of data assimilation methods, such as Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) can directly provide physical parameter estimations of nonlinear dynamic systems. The stiffness parameters are included in the state vector; the parameters are estimated as a part of the augmented state vector. UKF, which has been shown to be superior to EKF because UKF can deal with up to the second order of nonlinearity, however, has never been validated using laboratory or in-situ measurements.

Common problem which prevents application of data assimilation methods to full-scale bridges is the lack of robustness and the data. UKF requires initial process and measurement noise covariance matrices to be known a-priori and keeps both matrices constant over time. If these matrices are not known, UKF performs sub-optimal or even diverges. In addition, UKF is also sensitive to initial state vector assignments. These problems become severe in particular when the size of the state vector is large. Thus, in order to practically apply UKF to structural identification, estimation methods addressing these robustness issues are needed. Furthermore, seismic response monitoring has been limited to some signature bridges where sensor networks are readily available. The number of channels is also limited. Seismic response data to be utilized in the data assimilation methods is rare.

This thesis first prepares seismic response measurement data to be utilized in the stiffness condition assessment of full-scale bridges and proposes the use of the Robbins-Monro stochastic approximation scheme with UKF (UKF-RM) for the stiffness estimation problems to address the robustness issues. The performance of the proposed algorithm is then examined through simulations and measured records. Lastly, the UKF-RM is extended to hysteresis loop estimation of structural elements under non-linear motion.

To study the applicability and robustness of data assimilation techniques, the availability of seismic response data is essential. The large-scale laboratory test on an RC concrete pier and in-situ measurement of earthquake responses, which provide data sets the proposed algorithm is investigated with, are first explained. The shake table test on an RC pier conducted at the E-Defense facility provides detailed dynamic motion records during a variety of ground excitations. The pier is equipped with numerous accelerometers, displacement sensors, and load-cells; input and output records are all available together with data to validate the structural identification results. Movies and detailed description of the pier during the excitation are also available; stiffness identification results can be interpreted with these detailed information. The in-situ measurement, on the other hand, was made possible with the recent advance in the wireless sensor technologies. Wireless sensor nodes with low cost, weeks-long battery life, and seismometer-class high quality sensors made the detailed seismic response measurements on ordinary bridges possible. Using the wireless sensors, shortly after April 2016 Kumamoto Earthquake, a 60 m span steel box girder bridge was instrumented. The bridge sits on rubber bearings. Over a period of two weeks, 61 seismic response records had been obtained. Records were obtained on pier, abutment, and corresponding girder locations. These records provide input and output information of the rubber bearing system.

Consequently, the use of the Robbins-Monro stochastic approximation scheme with UKF (UKF-RM) has been proposed and numerically investigated. Through simulations UKF-RM scheme is shown to significantly improve the robustness of the filter when compared to conventional UKF. The performance is investigated in detail through simulations considering changes in initial process, measurement, and error covariance matrices, initial state vector, measurement noise, and UKF-RM parameter α. The sensitivities of the UKF-RM approach to the changes are shown low. In addition, since UKF-RM adapts noise covariance during estimation, its convergence rate is fast. The change in stiffness during nonlinear responses is traceable with UKF-RM.

The method has been further validated using laboratory experiments on a reinforced concrete bridge column with response measurements from small and large earthquakes. Experimental validation of the proposed algorithm is presented using measurement records from shake-table laboratory tests of linear and nonlinear response levels. In both cases, UKF-RM proved to be faster in convergence than the conventional UKF. The proposed method is capable of tracing the stiffness change of nonlinear behavior. This application is the first example of a stiffness condition identification of a 1:1 scale bridge lateral resisting system component, an RC pier, using UKF-RM.

The method is then validated using the in-situ measurement seismic response data. The stiffness condition of the rubber bearings has been investigated with the proposed UKF- RM method. The stiffness coefficients of the bearings on the pier and on the abutment have been successfully obtained considering multi-support excitation. The identified stiffness coefficients are shown consistent with factory testing results.

Lastly, hysteresis response identification only using acceleration measurements are proposed by employing the UKF-RM approach together with numerical integration of the acceleration records. As the nonlinear model, non-degrading conventional Bouc-Wen model is employed; the hysteresis is estimated by identifying the augmented state vector including the non-linear parameters. First, the observability analysis was performed. To make the system observable even when only one response observation in addition to the ground motion is available, the reduction of the Bouc-Wen model is shown necessary. The model is reduced considering the practical conditions of the target structure. Then, the algorithm performance to identify the parameters of the reduced model and the hysteresis loop was investigated numerically. UKF-RM results in more robust and stable parameter estimations than the conventional UKF. The effect of neglecting residual displacement due to the high-pass filtering associate with the acceleration integration is investigated; the effect of residual displacement on total energy dissipation is shown small. Except for the energy dissipated by the residual displacement, the hysteresis response obtained with UKF-RM using double-integrated acceleration as observation contains the hysteresis cycles where most of the energy from the input excitation is dissipated by the RC pier. Finally, hysteresis response identification with Bouc-Wen model using only acceleration measurements with UKF-RM algorithm was validated using measurement from the shake table test. The hysteresis estimated from the acceleration signals is shown consistent with the hysteresis directly measured using displacement sensor and load-cells.