Uncertainty Quantification of Complex Nonlinear Systems using Structural Health Monitoring Techniques

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Abstract

Structural Health Monitoring (SHM) is a multidisciplinary field used to monitor the health conditions of structures and predict damage in its early stages using periodically spaced real-time observed measurements. The presence of different sources of significant uncertainties, mainly due to model errors, parametric variability and measurement data inadequacy, is inevitable when modeling nonlinear dynamical systems with physical complexities. Therefore these uncertainties must be accurately quantified and represented within the mathematical framework of Structural Health Monitoring methods, to reduce failure risks through early detections of damage and to improve identification of the unknown system responses and parameters.

In this study, two different variants of the Kalman Filter (KF) method, the ordinary Ensemble Kalman Filter (EnKF) method and the Polynomial Chaos based Ensemble Kalman Filter (PCKF) method, are implemented for uncertainty quantification and system identification purposes. While the EnKF method is based on Monte Carlo simulation and uses a black-box model to propagate an ensemble of realizations forward in time, the PCKF approach propagates the polynomial chaos representations of the unknown states and parameters to identify the system responses and detect the damage.

The performance and robustness of both variations of the Kalman Filter technique are tested on a numerical example consisting of a nonlinear multi-degrees-of-freedom system, undergoing hysteretic behaviors and subjected to earthquake ground excitation. The displacements and velocities of each degree-of-freedom and the unknown parameters of the system are respectively estimated using both Kalman Filter based SHM frameworks, and then compared with the corresponding true system state values. The comparison of the two techniques is thus based on the accuracy of the predicted results compared to the respective actual measured data, the computational burden of the simulation runs required by each method, and the ability of each technique to represent and quantify the system uncertainty to enhance Structural Health Monitoring for damage detection.

The results show that both frameworks of the Kalman Filter method are able to correctly detect the damage and to accurately estimate the unknown system responses and parameters. While the Ensemble Kalman filter framework is easier to implement, the Polynomial Chaos Kalman Filter method outperforms the standard Ensemble Kalman Filter technique in terms of computational effort for comparable levels of numerical accuracy.

Keywords: Uncertainty Quantification; Nonlinear Dynamics; System Identification; Structural Health Monitoring; Kalman Filtering