Novel Unscented Kalman Filter for Health Assessment of Structural Systems with Unknown Input

Abdullah Al-Hussein, A.M.ASCE[1]; and Achintya Haldar, Dist.M.ASCE[2]

Abstract: A novel procedure for structural health assessment, denoted as unscented Kalman filter with unknown input (UKF-UI), is proposed using the nonlinear system identification concept. To increase its implementation potential, a substructure concept is introduced, producing a two-stage approach. It integrates the unscented Kalman filter concept and an iterative least-squares technique. The two most important features of the method are that it does not need the information on the time history of the excitation to identify structural systems represented by finite elements, and that it can identify defects in them using only a limited amount of noise-contaminated nonlinear response information. The proposed method is robust enough to detect the locations and severity of defects at different locations in the structure. The defect detection capability increases significantly if the defective member is in the substructure or close to it. The method is conclusively verified with the help of two examples using impulsive and seismic excitations. The superiority of UKF-UI over extended Kalman filter-based procedures is documented. The proposed UKF-UI procedure has high implementation potential and can be used for health assessment of large structural systems. **DOI: 10.1061/(ASCE)EM.1943-7889.0000926.**

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Introduction

Civil infrastructure systems are expected to deteriorate with time and continuously accumulate damage throughout their service life owing to the natural aging process and/or a lack of adequate maintenance. They may also experience sudden damage due to natural hazards or manmade events such as explosions. If damage is left undetected and unmitigated, it could potentially cause more damage and eventually lead to catastrophic structural failure with loss of human life and severe economic consequences if the structure is put partially or completely out of service to mitigate the situation. To ensure the serviceability and safety, structural damage detection is necessary at the earliest possible stage. However, at present we do not have well-accepted inspection procedures to objectively detect locations of defect spots and severity of the defects.

Many civil infrastructures (CI) all over the world are in service for an extended period of time, and some of their operating periods have exceeded their design lives. Most of them were built conforming to old design standards; they are not expected to satisfy up-to-date design guidelines and other safety requirements. According to the ASCE (2013) *Report Card for America's Infrastructure*, the nation's infrastructure received an overall grade of $D+$, and the estimated investment needed to bring it up to the current standard would be $3.6 trillion by 2020.

Structural health assessment (SHA) is an age-old problem, and several methods with various degrees of sophistication are available (Doebling et al. 1996; Sohn et al. 2004). To detect defects at the local element level and their severity, the authors and their team, after conducting an extensive literature review, decided to use the vibration-based system identification (SI) concept for SHA. A basic vibration-based SI approach has three essential components: (1) excitation force(s); (2) system to be identified, generally represented in an algorithmic form such as by FEs; and (3) output response information measured by sensors. Using information on the excitation and responses, the system parameters of all elements can be identified using SI-based approaches. By comparing the identified stiffness parameters of all the elements with the design or expected values for similar elements or changes from the previous values if periodic inspections were conducted, the locations and severity of defects can be established, providing information on the current health of the structure.

Most CI systems behave nonlinearly; therefore, an ideal SHA should be based on the nonlinear SI concept. However, nonlinear SI is not easy. The problem is further complicated considering several implementation issues. The input excitation was assumed to be known in many previous studies (Wang and Haldar 1994). Outside the controlled laboratory environment, measuring input excitation force(s) can be very expensive and problematic, and can be expected to be highly noise-contaminated. This may make an SI-based concept inapplicable. Identifying a CI while ignoring the information on the excitation time history will add another layer of difficulties because two of the three basic components of the SI process will be unknown, assuming response information will be available at all dynamic degrees of freedom (DDOFs). However, for large, complicated CIs, it may not be practical or economically possible to measure response information at all DDOFs. Only a few floors of a large multistory building can be instrumented. Thus, the basic task will be to identify a large CI using only limited measured responses.

The most fundamental challenge of using SI-based procedures for SHA using measured dynamic response information was raised by Maybeck (1979). He correctly pointed out three basic reasons: (1) no mathematical model to represent a system is perfect;

[1]Doctoral Student, Dept. of Civil Engineering and Engineering Mechanics, Univ. of Arizona, Tucson, AZ 85721. E-mail: abdullaa@email.arizona.edu

[2]Professor, Dept. of Civil Engineering and Engineering Mechanics, Univ. of Arizona, Tucson, AZ 85721 (corresponding author). E-mail: haldar@u.arizona.edu

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