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Structural health assessment at a local level using minimum information

Abdullah Al-Hussein [1], Achintya Haldar *

Department of Civil Engineering and Engineering Mechanics, University of Arizona, P.O. Box 210072, Tucson, AZ 85721, USA

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ABSTRACT

A novel structural health assessment (SHA) technique is presented in this paper. It is a finite element-based time-domain nonlinear system identification technique. It can assess structural health at the element level using only a limited number of noise-contaminated responses and without using information on input excitation. It assesses the location and severity of defect(s) by tracking the changes in the stiffness properties of individual elements from their expected values. The procedure integrates an iterative least squares technique and the unscented Kalman filter (UKF) concept. The integrated procedure significantly improves the basic UKF concept. To demonstrate the effectiveness of the procedure, the health of a relatively large structural system under single and multiple excitations is assessed. Small and relatively large defects are introduced at different locations in the structure and the capability of the method to detect the health of the structure is examined. The optimum number and location of measured responses are investigated. It is demonstrated that the method is capable of identifying defect-free and defective states of the structures using minimum information. Furthermore, it can locate defect spot within a defective element. It is also demonstrated that the proposed method, denoted as UKF-UI-WGI, is superior to the extended Kalman filter-based procedures for SHA developed by the team earlier.

1. Introduction

Civil infrastructure systems, such as buildings and bridges, begin to deteriorate once they are built and used. They also suffer different levels of damage when exposed to severe events, like strong earthquakes, high winds, etc. Even well designed structures can suffer damage due to faulty construction or when exposed to unexpected loadings. Some of the civil infrastructures built conforming to old design standards or guidelines are currently in operation and over their design life. They are especially susceptible to damage because of natural degradation with age and may not satisfy the current design and construction standards. If damages go undetected for an extensive period of time, even a minor defect can become severe causing catastrophic failure leading to loss of life or the repair cost can be prohibitive and replacement will be the only option. However, resources available to the world communities are very limited at present and replacement is not a desirable option. The most attractive option is to extend the life of current infrastructures by identifying the location, type, and severity of defects and then repairing them using the appropriate methods.

Visual inspection is routinely used to assess structural health at present. However, visual inspections may not be conclusive. They are expected to be dependent on the expertise of the inspector. In some cases, defects may be hidden behind obstructions like fire proofing materials, false ceiling, etc. or inaccessible. If the location and type of defects are known, we have technological sophistication to study them further by conducting localized experimental investigations using radiographs, magnetic, ultrasonic, etc. methods. To implement these types of inspection requires that the approximate location and type of damages are known a *priori*. Obviously, they are expected to be unknown for large infrastructures in most cases.

The necessity of cost-effective damage detection techniques suitable for large complex infrastructures has led to the development of several multi-disciplinary methods for structural health assessment (SHA). For the health assessment of civil infrastructures, both static and dynamic response information can be used. When dynamic response information was used, both modal and time domain approaches were pursued. Because of its numerous superiorities, time domain SHA has received significant attention by the researchers recently. Many techniques also have been developed to identify structural systems specifically for SHA [1–3].

To identify defect locations accurately, it would be efficient to represent the structure by finite elements. By tracking the stiffness of the elements, the location and severity of the defects can be assessed. It will also be very desirable if a structure can be

* Corresponding author. Tel.: +1 (520) 621 2142; fax: +1 (520) 621 2550.
E-mail addresses: abdullaa@email.arizona.edu (A. Al-Hussein), haldar@u.arizona.edu (A. Haldar).
[1] Tel.: +1 (520) 621 2266; fax: +1 (520) 621 2550.

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identified using only measured response (acceleration) time histories completely ignoring the excitation time history. Outside the laboratory condition, measuring excitation time history can be very difficult. It may be severely noise-contaminated and the SI-based SHA techniques may not be appropriate. The information on excitation may not also be available just after a natural event like earthquake for the rapid assessment of structural health. For large infrastructures, it may not be practical or economical to measure response time histories at all dynamic degrees of freedoms (DDOFs). Only a part of the structure can be instrumented and thus responses will be measured at a limited number of DDOFs. Furthermore, all sensors used to record response time histories are expected to introduce noise of unknown magnitude in the measurement. In summary, the health of large structural systems needs to be assessed by implementing time domain SI-based concept using only limited number of measured noise-contaminated responses without using any information on excitation.

Considering all these features, the team proposed several methods for SHA using the extended Kalman filter (EKF). EKF is the most widely used state estimation algorithm for nonlinear systems. The team developed several EKF-based SHA procedures and verified them theoretically [4–7] and experimentally [8–11]. Although the EKF has been successfully used to assess structural health in many applications, it has several shortcomings. EKF operates by approximating the state distribution as a Gaussian random variable (GRV) and then propagate it through the first-order linearization for the nonlinear system [12]. The EKF-based approach provides only an approximation to the optimal nonlinear filter due to the truncation of the higher-order terms when linearizing the system. In practice, EKF suffers two well-known drawbacks. First, the derivation of the Jacobian matrices required to implement the filter is nontrivial in most applications and often lead to significant difficulties. Second, the filter can be unstable if the sampling interval or time between two samples is not sufficiently small. There may be a threshold of nonlinearities when EKF may not be able to identify a system for SHA. An alternative to EKF is UKF, particularly for highly nonlinear SI. UKF was developed with the underlying assumption that approximating a Gaussian distribution is easier than approximating an arbitrary nonlinear transformation [13]. UKF uses deterministic sampling (or so called sigma points) to approximate the state distribution as a GRV. The sigma points are chosen to capture the true mean and covariance of the state distribution. They are propagated through the nonlinear system. The posterior mean and covariance are then calculated from the propagated sigma points. UKF determines the mean and covariance accurately to the second order, while EKF is only able to obtain the first-order accuracy [12]. Therefore, UKF provides better state estimates for nonlinear systems.

UKF has been successfully applied to numerous practical problems and it has been shown to outperform EKF in many cases including target tracking and vehicle navigation, training of neural networks, and position determination. Although UKF has been applied to a wide range of estimation problems, it has not been applied widely in the field of civil engineering. Most of the applications are for identifying structures with few dynamic degrees of freedom (DDOFs). Mariani and Ghisi [14] applied UKF for a case of softening single DDOF structural systems. Wu and Smyth [15] applied UKF to a single DDOF nonlinear hysteretic dynamic system, a 2DDOF linear system, and a 2DDOF nonlinear elastic system. Chatzi and Smyth [16] applied UKF for unmeasured state and modal parameter identification of 3DDOF systems with Bouc-Wen oscillator. The available structural system identification procedures using UKF were essentially developed and verified for simple structures represented by shear-type buildings with small numbers of DDOFs. Another weakness of these studies is that at least one of measured dynamic responses (displacement, velocity, or acceleration) is assumed to be available at all DDOFs. It is not practical to measure dynamic responses at all DDOFs for a large complicated structure. Furthermore, in these applications the input excitation is assumed to be known. As mentioned earlier, measuring excitation information accurately is a major challenge even in the controlled laboratory environment. It will be a major challenge if excitation information needs to be measured for real existing structures in field conditions. Also, the application of UKF in the context of defect assessment is not addressed. The determination of location of defects and their severity are needed for SHA. The authors addressed these deficiencies and are in the process of developing a novel procedure denoted as Unscented Kalman filter with Unknown Input and Weighted Global Iteration (UKF-UI-WGI). The procedure integrates UKF with an iterative least-squares technique in order to widen its application potential in identifying a structure with limited response information. A substructure approach is also incorporated in the proposed procedure. Furthermore, in order to obtain the stable and convergent solutions, a weighted global iteration procedure with an objective function is introduced into the UKF algorithm.

SHA using the UKF-UI-WGI procedure is demonstrated with the help of realistic structures with large DDOFs in this paper. The optimum number and location of dynamic responses required to identify structural parameters are studied. Both defect-free and defective states are considered. The capabilities of the method are checked by considering different levels of severity of defect. Its capability is also checked if it can identify the defect spot within a defective member. It is observed that it is capable of assessing structural health in the presence of different defect scenarios. The locations of defects with respect to the available limited measured response information are also investigated. As expected, the accuracy of the defect identification improves significantly if the measurement points are close to the defect location. To demonstrate the effectiveness of the proposed procedure, the results of UKF-UI-WGI are compared with the EKF-based procedures already developed by other team members.

2. Concept of UKF-UI-WGI procedure

As mentioned earlier, the unscented Kalman filter (UKF)-based algorithm can be used for nonlinear system identification. It is generally used when the response information is limited and noise contaminated. The use of UKF also helps to incorporate error in the basic mathematical model representing the structure as well as the presence of noise in the measured responses. However, it has three fundamental weaknesses that limit its use for SHA. To satisfy the dynamic governing equations, the excitation information must be known. However, for broader application potential, as mentioned earlier, it should be considered unknown but it introduces a major hurdle. Also, UKF-based approaches require that the initial state vector for the whole structure is known; obviously it will be unknown at the beginning of the inspection. The third weakness is that the basic UKF algorithm may not able to identify a large structural system. The discussions clearly indicate that the basic UKF-based method available in the literature cannot be used broadly for SHA; the concept needs to be improved.

To identify large structural systems with limited measured response information and unknown input, a two-stage approach is used. In Stage 1, based on the locations of input excitation and measured responses, a substructure can be defined. Then, using only information of the measured responses at the substructure, the input excitation can be identified using iterative least squares with unknown input (ILS-UI), developed by Wang and Haldar [17] and modified by Katkhuda and Haldar [18]. In addition, the stiffness parameters of all the elements in the substructure and