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Probability-based damage detection using model updating with efficient uncertainty propagation

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ABSTRACT

Model updating method has received increasing attention in damage detection of structures based on measured modal parameters. In this article, a probability-based damage detection procedure is presented, in which the random factor method for non-homogeneous random field is developed and used as the forward propagation to analytically evaluate covariance matrices in each iteration step of stochastic model updating. An improved optimization algorithm is introduced to guarantee the convergence and reduce the computational effort, in which the design variables are restricted in search region by region truncation of each iteration step. The developed algorithm is illustrated by a simulated 25-bar planar truss structure and the results have been compared and verified with those obtained from Monte Carlo simulation. In order to assess the influences of uncertainty sources on the results of model updating and damage detection of structures, a comparative study is also given under different cases of uncertainties, that is, structural uncertainty only, measurement uncertainty only and combination of the two. The simulation results show the proposed method can perform well in stochastic model updating and probability-based damage detection of structures with less computational effort.

1. Introduction

In the past few decades, sensitivity-based finite element (FE) model updating methods have been widely investigated [1–3], and successfully applied in the damage detection [4–6] of structures based on experimentally measured modal parameters. In these methods, damage is identified by minimizing the differences between the analytically FE computed and experimentally measured data through updating the physical variables and using sensitivity derivatives of modal parameters with respect to physical variables. It is reasonable that modal parameters are often used in damage detection [7–9], because not only modal parameters (modal frequencies, mode shapes) are functions of the physical parameters (mass, stiffness) and the existence of damage may lead to changes in the modal properties of the structure, but also modal parameters can be measured conveniently and accurately. In the most application of model updating on damage detection, the experimentally measured modal parameters are considered to be exact and deterministic.

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In reality, however, there are always uncertainties in the measured modal parameters which may lead to unreliable and false prediction of structural damage, and, as a result, it is necessary to consider the uncertainties in damage detection of structures [10–12]. In general, there are two sources for the uncertainties in measured modal parameters. First, uncertainties is introduced in modal parameters by the inherent variability or randomness in structural parameters (physical material properties, geometric parameters), which cannot be reduced or eliminated by the knowledge or techniques available. Second, uncertainties in modal parameters arise from the measurement noise and modal identification techniques. This kind of uncertainties in modal parameters can be hopefully reduced, but not be eliminated, by more precise measurement instrumentation and more appropriate modal identification techniques. In the case of uncertain measured modal parameters, the probabilistic approaches are frequently used for incorporating structural uncertainties and measurement noise in the damage detection by generally describing the uncertainties as random variables characterized by mean values and standard deviations [13–17].

Recently, the stochastic FE model updating methods have received more and more attention. In stochastic FE mode updating, the updated parameters are no longer deterministic and they are described as random values with their mean values and covariance matrices, given the distribution functions of known input (measured modal parameters). In the earlier works, the statistic method, only incorporating the measurement noise into model updating, is given by Collins et al. [18] and Friswell [19]. Later, the FE model updating methods were developed in the Bayesian probabilistic framework by Beck et al. [20–22]. Recently, perturbation methods have been effectively employed in stochastic model updating [23–26], in which random variable vectors are used as the perturbation to parameter means in model updating equations including deterministic terms. In the literatures of perturbation-based model updating, Hua et al. [24] developed two recursive systems of equations for estimating the first two moments of random structural parameters from the statistics of the measured modal parameters using the first-order perturbation method and sensitivity-based FE model updating. Friswell et al. [25] developed two versions of perturbation approach to the stochastic model updating problem with test-structure variability. The correlation between the updated parameters and measured data is omitted in one version, and included in another version. It is shown that, compared to the results by Hua et al. [24], the first version is acceptable which requires only first-order derivatives. It is worthy to note that Hua et al. [24] worked in terms of the sensitivity matrix, requiring the evaluation of the second-order derivatives and time-consuming, rather than the transformation matrix used in Friswell's work [25].

As part of the updating procedure, forward uncertainty propagation is required in every iteration step of stochastic updating. The first-order perturbation method (FOPM) [26] and the Monte-Carlo simulation (MCS) method [27] are the two commonly used approaches to uncertainty propagation. Compared to the MCS method frequently chosen as a scheme to verify a new methodology, which is the most accurate but is computationally expensive and extremely time-consuming, the FOPM has been widely used for its tractability and computational time-saving. In the perturbation method, however, small variability in parameters is required, and the derivatives of dynamic modal parameters with respect to the random variables should be evaluated, which may become very difficult for large-scale structures with a large amount of degrees of freedom. In addition, the mean of random function is calculated only by the first-order derivatives and means of corresponding variables, without considering the co-variances of variables since the second-order derivatives are omitted in FOPM.

The main idea of random factor method (RFM) developed by Chen and his co-workers [28–30], in which any random variable is expressed as the product of its mean and a random factor instead of the sum of its mean and zero mean random variable traditionally used in FOPM, has been used to analyze the dynamic characteristics and response of structures with random parameters. In RFM, specially, the statistical characteristics of modal parameters can be explicitly expressed by those of random parameters, and, as a result, analytically evaluated with less computational efforts. In literatures available, all the studies are on the assumption of homogeneous random field, which means the randomness is previously considered to be the same for all elements. In the iterative process of stochastic model updating, however, the randomness of updating parameters is not the same and keep changing. In this article, the random factor method (RFM) for non-homogeneous random field is developed and used to analytically evaluate covariance matrices in each iteration step of stochastic model updating. The remainder of this article is organized as follows. First, the general stochastic FE model updating method is introduced, and a computationally efficient optimization algorithm for constrained problems is presented. Next, the RFM for non-homogeneous random field and its approximation for computation are developed, in which the dynamic characteristics (modal frequencies and mode shapes) are formulated as the functions of random factors of random variables, and their statistical characteristics can be analytically obtained by explicit expression. Then, probability-based damage detection method is given by calculating the probability of damage existence. Finally, the developed algorithm is illustrated by a simulated 25-bar truss structure and a comparative study is given between the proposed method and the MCS method.

2. Theoretical background

2.1. Sensitivity-based method

Generally, sensitivity-based FE model updating method can be posed as a minimization problem in which the physical parameters of a FE model are adjusted and updated such that analytically computed features (typically, modal parameters) obtained from the updated FE model are consistent with those obtained from measurements. To this end, the objective