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A stochastic model updating strategy-based improved response surface model and advanced Monte Carlo simulation

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ABSTRACT

To improve the accuracy and efficiency of computation model for complex structures, the stochastic model updating (SMU) strategy was proposed by combining the improved response surface model (IRSM) and the advanced Monte Carlo (MC) method based on experimental static test, prior information and uncertainties. Firstly, the IRSM and its mathematical model were developed with the emphasis on moving least-square method, and the advanced MC simulation method is studied based on Latin hypercube sampling method as well. And then the SMU procedure was presented with experimental static test for complex structure. The SMUs of simply-supported beam and aeroengine stator system (casings) were implemented to validate the proposed IRSM and advanced MC simulation method. The results show that (1) the SMU strategy hold high computational precision and efficiency for the SMUs of complex structural system; (2) the IRSM is demonstrated to be an effective model due to its SMU time is far less than that of traditional response surface method, which is promising to improve the computational speed and accuracy of SMU; (3) the advanced MC method observably decrease the samples from finite element simulations and the elapsed time of SMU. The efforts of this paper provide a promising SMU strategy for complex structure and enrich the theory of model updating.

1. Introduction

In engineering simulation analysis, it is always difficult for the established model to accurately simulate real engineering problem. The precision improvement of simulation model has resulted in the development of model updating technology [1]. Finite element model updating (FEMU) is one important model updating technique to reduce the error between the finite element (FE) model and the corresponding real-structure in the light of test data. As an inverse optimal problem, structural FEMU method gets a rapidly development recently. Friswell [2,3], Peter et al. [4], studied on the FEMU in structural dynamics and adjusted structural parameters using a minimum variance estimator; Zapico-Valle et al., advanced a new FEMU in structural dynamics [5]; Ahmadian et al., developed the modeling and updating methods for large surface-to-surface joints in the awe-mace structure [6]; Modak, focused on the model updating using uncorrelated modes [7]; Jin et al., proposed a new multi-objective approach for FEMU [8]. Besides, genetic algorithm is also applied to FEMU and dynamic FEMU [9,10]. From the above efforts, the existing updating methods are deterministic model updating which regards the

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influencing parameters as the specific values.

In fact, uncertainties are ubiquitous and inevitable in many aspects of geometric sizes, manufacture, assembling, joint stiffness design, material property, and so forth [11–13], which promote the emergence of uncertain analysis method with respect to uncertain parameters. Roy et al., given an overview of a comprehensive framework with respect to uncertainties [14]; Park et al., discussed the quantification of model uncertainty using Bayesian approach [15]; Fonseca et al., completed uncertainty identification by the maximum likelihood method [16]; Schuëller et al., studied on the uncertainty analysis of a large-scale satellite FE model [17]. To improve the precision of FEMU, the relative theories and method were also developed for stochastic model updating (SMU) with the consideration of random and uncertain factors [18]. For instance, Mares et al., investigated the theory and application of SMU [19,20]; Husain et al., adopted the perturbation method to study SMU [21]; Bao et al., presented a Monte Carlo (MC) simulation-based inverse propagation method for SMU [22]; Beck et al., focused on Bayesian updating of structural models and reliability using Markov Chain MC simulation [23]; Rui et al., proposed an efficient statistically equivalent reduced method for stochastic model updating [24].

However, for complex structure with large-scale uncertain parameters, the FEMU is unacceptable due to low computational efficiency for an excess of FE simulations and superabundant loop computation. It is urgent to seek a new model updating method to improve computational efficiency. One viable alternative to FE model is response surface (RS) method, which needs less FE calculations and holds rapid simulation of RS function, and has been employed to deterministic model updating without considering uncertain parameters by Ren [25,26], Chakraborty [27] and Fang [28]. Recently, RS method was applied to the SMU of uncertain parameters to select important parameters as updating variables by probabilistic analysis [29]. For example, Fang et al., proposed a SMU method for parameter variability quantification based on RS method and MC simulation [30] and also investigated the parameter variability estimation using stochastic RS model updating [31]; Romero et al., constructed a RS model for uncertainty propagation based on progressive-lattice-sampling experimental design [32]; besides, artificial neural network and Kriging model were investigated for RS model updating [33,34].

Currently RS method-based least-square method (LSM) is frequently-used and extensively studied, however, many shortages exist yet for the SMU of complex structure: (1) prior information is not utilized for the existing RS methods which limit the application of RS methods, so that RS model-based LSM is unable to perfectly approximate the real-structure model [27]; (2) traditional MC simulation methods used widely in SMU-based RS method has no memory capability on random sampling for input variables. Therefore, it is possible that the accuracy of SMU for complex structure is unaccepted. For the first issue, based on structural mechanics equations and dimensional analysis principle, the improved RS model (IRSM) is proposed based on moving least-square method (MLSM) by takes a full consideration of the relationship between mathematical and physical principles, the laws of statistics and the prior (posterior) information, which attempts to make the RS function closer to the mechanism model of real-structure and then improve the precision of SMU. Additionally, MLSM remedies the insufficiency of LSM [27], which is towardly to establish the high-precision RS model of complex structure. For the second one, an advanced MC simulation with Latin hypercube sampling method (LHSM) is presented to extract the samples of random parameters (uncertainties) which requires less samplings for fitting RS function and potentially improve computing speed owe to avoid repeated sampling for memory ability [35].

Dynamic measurements have been proved to be valid in providing valuable reference data for FEMU [3,17]. However, it is difficult to separate modeling errors from stiffness-related variables and mass-related variables. Static data have only related with stiffness rather than mass parameters so that the precision of static data is ensured [25]. If more response information is provided, the updated model built-based static data holds high-precision and high-reliability because the static data are easily achieved and affected by noise level [27]. Therefore, the structural static responses are important and necessary for a successful and reliable SMU.

The objective of this paper is to attempt to explore a SMU strategy based IRSM-based MLSM and advanced MC simulation-based LHSM by using structural static responses. The proposed methods were applied to the SMUs of simply supported beam and aeroengine stator system (casings) based on the measured static responses. By the SMUs, the IRSM and advanced MC simulation are demonstrated to be effective and reasonable in improving the precision and efficiency of the SMU of complex structure.

In what follows, Section 2 investigates the basic theory of SMU including IRSM-based MLSM and advanced MC simulation. In Section 3 the SMU procedure is given. Section 4 focuses on the SMU and validation of simply supported beam based on the proposed method. The SMU and validation of aeroengine stator system are implemented in Section 5. The main conclusions are given in Section 6.

2. Basics theory for stochastic modeling updating

2.1. Improved response surface method, IRSM

In this subsection, the IRSM is developed based on MLSM and prior information. MLSM is used to search for the efficient coefficients of RS model. Prior information is applied to establish the reliable RS model.

An advanced method for regression is MLSM, which introduces a weighted LSM that has various weights with respect to the position of approximation. Therefore, the coefficients of a RS model are functions of the location and hereby should be calculated for each location. This procedure is interpreted as a local approximation [36]. The basic principles of LSM and