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Parameter variability estimation using stochastic response surface model updating

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ABSTRACT

From a practical point of view, uncertainties existing in structural parameters and measurements must be handled in order to provide reliable structural condition evaluations. At this moment, deterministic model updating loses its practicability and a stochastic updating procedure should be employed seeking for statistical properties of parameters and responses. Presently this topic has not been well investigated on account of its greater complexity in theoretical configuration and difficulty in inverse problem solutions after involving uncertainty analyses. Due to it, this paper attempts to develop a stochastic model updating method for parameter variability estimation. Uncertain parameters and responses are correlated through stochastic response surface models, which are actually explicit polynomial chaos expansions based on Hermite polynomials. Then by establishing a stochastic inverse problem, parameter means and standard deviations are updated in a separate and successive way. For the purposes of problem simplification and optimization efficiency, in each updating iteration stochastic response surface models are reconstructed to avoid the construction and analysis of sensitivity matrices. Meanwhile, in the interest of investigating the effects of parameter variability on responses, a parameter sensitivity analysis method has been developed based on the derivation of polynomial chaos expansions. Lastly the feasibility and reliability of the proposed methods have been validated using a numerical beam and then a set of nominally identical metal plates. After comparing with a perturbation method, it is found that the proposed method can estimate parameter variability with satisfactory accuracy and the complexity of the inverse problem can be highly reduced resulting in cost-efficient optimization.
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1. Introduction

For most real-world problems, engineers must deal with different kinds of uncertainties such as unknown model boundary conditions and measurement noises for right decisions [1]. At the moment deterministic analyses are no longer reliable and thus statistical techniques should participate in the solutions of such problems. In the realm of FE model updating, most existing methods possess deterministic inherence without taking uncertainty factors into account [2]. This situation motivates the involvement of probabilistic methods in model updating for the solution of an inverse problem [3]. Here a clear distinction between uncertainties and errors should be firstly made where uncertainty is defined as “a potential

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deficiency in any phase of activity of the modeling process that is due to lack of knowledge" [4]. In practice of structural dynamic analyses, this definition can be further refined into two categories of uncertainties, namely aleatory (irreducible) and epistemic (reducible) uncertainties [5]. The former refers to parameter variability caused by manufacturing tolerances and discreteness of material properties, which cannot be avoided or eliminated. But the latter one stems from lack of knowledge (e.g., a limited number of measurements or lack of structural information), which can be reduced by increasing the relevant knowledge. It is noted that in many practical cases a strict boundary cannot be defined between the two categories. On the other hand, methods for uncertainty propagation can also be divided into three categories of probabilistic, fuzzy and interval methods [6], among which the first category is within the scope of this study.

At the early stage of the research in uncertainty quantification, reducible uncertainties received close attentions [7–14]. Firstly the minimum variance methods were formulated by assuming that structural randomness stemmed merely from measurement noises and the uncertainties were described as variances [7,8]. The inverse solution sought for parameter means whose best estimates were satisfied when the variance estimates were minimized. The correlations between parameter estimates and measurement errors became an essential factor since their independence assumption would lead to an unbiased, instead of minimum variance, estimator [8]. Later treatments of such reducible uncertainties through statistical model updating also relied on Bayesian statistical frameworks. Bayesian estimation was adopted for conditioning the updating problem where relative confidence measures were established for unknown parameters leading to a more reliable algorithm [9]. Deterministic structural models were embedded within a class of probability models and the initial joint probability distributions of unknown parameters were updated using the Bayes' theorem [10]. The identification of a class of probability models, rather than one model, embodies the superiority of Bayesian methods over minimum variance methods. Meanwhile, the Marcov Chain Monte Carlo method can be applied to Bayesian model updating for estimating complex posterior probability density functions with respect to small and high dimensional problems [11,12]. However, the complexity in problem solutions, as well as the requirement for high computational costs, also restrains the applications of Bayesian updating methods to complex problems. Therefore surrogate models such as polynomial chaos expansions (PCE) and Kriging models have been utilized to alleviate the computational burden [13,14]. More recent works related to Bayesian model updating can be found in [13] where a comprehensive Bayesian approach has been developed for complex problem solutions.

As to the quantification of irreducible uncertainties, stochastic model updating (SMU) procedures based on the maximum likelihood function formulated by using the Monte-Carlo (MC) or the mean-centered first-order perturbation methods have been developed by Fonseca et al. [15]. The parameter variability was quantified from experimental data by maximizing the likelihood of the measurements whose components' correlation was not considered. A similar but different MC based inverse procedure [16,17] has been developed for parameter variability quantification while the iterative nature of such methods could induce considerable computational cost. Alternatively, perturbation methods can be effectively integrated into an SMU process [18–20] for uncertainty propagation by expanding the updating equation terms with a truncated Taylor series expansion around certain parameter points. By overlooking the correlation between parameters and measurements, the calculation for second-order sensitivities [19] can be avoided resulting in a simplified procedure [20]. Perturbation based methods show their superiority over MC based methods in the aspect of computational efficiency. However, when facing complex problems they also suffer from their applicability of small uncertainties and the prerequisite of a Gaussian distribution assumption. Moreover, parameter predictions are sensitive to the initial estimates of parameters and their distribution ranges. Besides the aforementioned methods, a classic model updating technique can also be extended through an equation involving the statistical properties of parameters [21]. But the iterative inherence of the inverse solution procedure would still restrain the practical application. Hence as an alternative option, an SMU process can be divided into a series of deterministic ones and the inverse problem is solved within a deterministic framework [22]. By this means the stochastic updating efficiency can be highly improved without losing estimation accuracy and precision.

This paper also focuses on quantifying parameter variability since so far the relevant research is few and thus deserves further exploration. As previously mentioned, the existing SMU methods have some drawbacks such as intensive computational costs and the complexity in the establishment and solution of stochastic inverse problems. Furthermore, sensitivity analysis during the inverse solution also increases the solution difficulty in view of appearance of an ill-conditioning problem. On account of these facts, the employment of surrogate models [22,23] and a proper updating strategy may be a solution. Under such consideration, this study correlates uncertain parameters and responses using stochastic response models (SRSMs) which are actually explicit PCEs based on Hermite polynomials [24]. During updating iterations, sensitivity computation is avoided by means of SRSM reconstruction and optimization operations can be performed directly on mathematical expressions. Another advantage consists in the fact that parameter means and variances are updated and estimated in a separate way. Namely, means representing the deterministic parts of parameters are firstly sought with unchanged (initial) variances. Then the variances representing the random parts are estimated with previously updated means that remain unchanged. Such strategy can simplify the updating procedure and simultaneously improve the estimation precision. In addition, parameter sensitivity analysis is implemented based on the derivatives of PCEs, by which the significance of uncertain parameters can be easily evaluated. Lastly the proposed methods have been validated using a numerical beam and then a set of nominally identical metal plates tested by Husain et al. [25,26] who performed a perturbation updating procedure for identifying the variability in the thicknesses and the material properties of the plates. The adoption of the same test data can compare the performance of the SRSM-based method and the perturbation-based method.

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