



Variance analysis for model updating with a finite element based subspace fitting approach

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ABSTRACT

Recently, a subspace fitting approach has been proposed for vibration-based finite element model updating. The approach makes use of subspace-based system identification, where the extended observability matrix is estimated from vibration measurements. Finite element model updating is performed by correlating the model-based observability matrix with the estimated one, by using a single set of experimental data. Hence, the updated finite element model only reflects this single test case. However, estimates from vibration measurements are inherently exposed to uncertainty due to unknown excitation, measurement noise and finite data length. In this paper, a covariance estimation procedure for the updated model parameters is proposed, which propagates the data-related covariance to the updated model parameters by considering a first-order sensitivity analysis. In particular, this propagation is performed through each iteration step of the updating minimization problem, by taking into account the covariance between the updated parameters and the data-related quantities. Simulated vibration signals are used to demonstrate the accuracy and practicability of the derived expressions. Furthermore, an application is shown on experimental data of a beam.

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1. Introduction

Linear system identification methods are of interest in mechanical engineering for modal analysis. Using output-only vibration measurements from structures, Operational Modal Analysis (OMA) has been successfully used as a complementary technique to the traditional Experimental Modal Analysis (EMA) methods [1–3]. With methods originating from stochastic system realization theory for linear systems, estimates of the modal parameters of interest (natural frequencies, damping ratios and observed mode shapes) can be obtained from vibration data. Among these methods, the stochastic subspace identification (SSI) techniques [4,5] identify the system matrices of a state-space model, from which the modal parameters are retrieved. Subspace methods are well-suited for the vibration analysis of structures in operation, which is due to the fact that they have excellent theoretical and computational properties, for instance numerical efficiency and robustness, see, e.g. [6,7].

For any system identification method, the estimated parameters are affected by variance errors due to finite data length, unknown excitation and measurement noise. The variance of the modal parameter estimates is a most relevant information for assessing their accuracy. It depends on the chosen system identification algorithm. A practical approach for the variance

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estimation of modal parameters was developed in [8], where an estimated covariance on the measurements is propagated to the desired parameters by considering a sensitivity analysis. The required sensitivities are derived analytically through first-order perturbation theory, from the data to the identified parameters, and are then computed using the system identification estimates. In [9], the covariance computation scheme for the covariance-driven subspace method (SSI-cov) has been developed, and in [10] a fast and memory efficient implementation of the covariance computation for SSI-cov has been proposed.

The identification of modal parameters or, more generally, the system identification results of a structure in operation find an important application in the calibration of a numerical model of the investigated structure. Finite element (FE) models are used, e.g. to verify design specifications, to assess stress fields in structures, to predict vibration levels under prescribed harmonic excitations, to detect abnormal structural behavior in the context of structural health monitoring [11,12], and so on. With model updating techniques, the parameters of the FE model are calibrated such that some model properties are close to the truly observed structural properties. Vibration-based FE model updating techniques [13,14] identify model parameters by minimizing a cost function involving the identified and model-based modal parameters (or derived variables thereof). The involved experimental data are subject to uncertainties. In a broad sense, these uncertainties can be classified into two categories of aleatory (irreducible) and epistemic (reducible) uncertainties [15]. Aleatory uncertainty may result from geometric dimension variability due to manufacturing tolerances or inherent variability of materials such as concrete, while epistemic uncertainty is caused by lack of knowledge (e.g. due to finite number of data samples, undefined measurement noises, unknown excitations, and so on). These uncertainties can be considered in two ways in model updating. First, the uncertainty of the updated parameters can be evaluated based on the uncertainty of the experimental data. Second, the uncertainty of the experimental data can be taken into account in stochastic updating techniques as suggested in [12]. In this paper, we consider the first way.

While many FE updating methods analyze the impact of aleatory structural uncertainties on the updated parameters (see for instance [16]), we consider the problem of evaluating the uncertainty of the updated FE parameters that result from the uncertainty when estimating parameters from vibration measurements. This statistical uncertainty falls into the category of epistemic uncertainties since it reduces as the number of measurements increases. We consider a recently proposed subspace fitting (SF) approach for FE model updating [17], which is a deterministic approach closely linked to subspace identification [18]. In this framework, the model parameters of a coarse FE mesh are updated in a minimization problem that consists in correlating a FE-based extended observability matrix with an experimental one that is identified from SSI-cov. Since the experimental observability matrix is estimated from measured vibration data, it is affected by uncertainty. In this paper, we propose a covariance analysis of the structural parameters obtained from the SF approach taking into account this uncertainty. The identified observability matrix and its covariance are estimated with SSI-cov [9,10] and propagated to the updated FE parameters by means of a sensitivity analysis. The expressions of the covariances of the FE parameters are an original contribution of the present paper. In particular, we show how the covariance originating from the vibration data is propagated through the iterations of the minimization problem for the solution of the FE parameters, taking into account the covariance between the parameter estimate in each iteration and the data-related quantities. The derived expressions are validated through Monte Carlo simulations. Notice that the covariance estimation from multiple datasets as in Monte Carlo simulations is computationally much more demanding [19], compared to the covariance estimation from a single dataset as in the proposed approach. Also, an application of the approach on a lab experiment is reported.

The paper is organized as follows. In Section 2, the theoretical framework of the FE-based SF method is presented. The covariance expressions of the updated FE model parameters are derived in Section 3. In Section 4, the covariance estimation procedure is illustrated regarding the vibration data issued from a numerical model of a beam. Results are validated with standard deviations obtained from Monte-Carlo simulations. Finally, in Section 5, the proposed method is applied to model updating using experimental data of a beam.

2. SF method for model updating

Model updating has the purpose to calibrate the parameters of a FE model such that some model properties are close to the truly observed structural properties. In the proposed SF method, the considered quantity for calibration is the extended observability matrix $\mathcal{O}$ of the underlying linear system. The main idea is to correlate – in a least squares sense – the matrix $\hat{\mathcal{O}}$ obtained from experimental data with the matrix $\mathcal{O}^h(\theta^h)$ issued from a FE model of the structure, where $\theta^h \in \mathbb{R}^{n_h}$ is the vector of structural parameters of the FE model to be updated.

In this section, the subspace identification method is introduced to obtain $\hat{\mathcal{O}}$ from experimental data, and the SF method, based on $\hat{\mathcal{O}}$ and $\mathcal{O}^h(\theta^h)$ for updating the vector of parameters θ^h is presented.

2.1. Stochastic subspace identification

The vibration behavior of a linear elastic structure, which is observed at some sensor positions, can be described through the following equations [1]

$$\begin{cases} \mathbf{M}\ddot{\mathbf{q}}(t) + \gamma\dot{\mathbf{q}}(t) + \mathbf{K}\mathbf{q}(t) = \mathbf{v}(t), \\ \mathbf{y}(t) = \mathbf{H}_d\mathbf{q}(t) + \mathbf{H}_v\dot{\mathbf{q}}(t) + \mathbf{H}_a\ddot{\mathbf{q}}(t) + \mathbf{w}(t), \end{cases} \quad (1)$$

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