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Improving the reliability of the frequency response function through semi-direct finite element model updating

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ABSTRACT

In this work, a scheme to enhance the reliability of the frequency response function (FRF) for structural dynamics by semi-direct model updating is reported. The proposed semi-direct updating method is a combination of iterative model updating and direct model updating schemes, and comprises three updating steps. First, to match analysis results with test results, the finite element (FE) model is updated with the conventional iterative model updating within the reasonable tolerance limit of eigenfrequencies and mode shapes. Second, to enhance the reliability of the FRF typically showing lower correlation with test results despite the first step model updating, the eigenfrequencies are replaced by the measured ones without updating corresponding eigenvectors. Then, the stiffness matrix is updated by a direct model updating scheme: matrix mixing approach with the mass matrix preserved. Finally, the unmeasured modal damping ratios are obtained by the minimization of FRF error function. As a result, FRFs obtained by the proposed scheme show excellent agreement with test data without losing mass properties together with the updated stiffness matrix reproducing the test data exactly. To demonstrate the accuracy and efficiency of the proposed method, two examples are prepared.

1. Introduction

Since the early 1990s, to enhance the accuracy of mathematical models in structural dynamics, research on the finite element (FE) model updating methods combined with vibration testing and optimization techniques has been actively pursued in academic and industrial fields in parallel with increased computing power. There have been numerous works on methodology, including direct methods and iterative methods [1,2]. In the direct methods, the stiffness and mass matrices are modified to reproduce the test data exactly, but such methods have little physical meaning due to excessive modification of the matrices. Also, they do not guarantee extra zero energy modes in the frequency range of interest. On the other hand, the iterative methods combined with sensitivity analysis have been widely adopted, but users have to set the parameters, such as mode pairing, proper correlation criteria, and so forth. However, setting the parameters is not so straightforward due to many uncertainties: the stiffness of joint and contact surface, the nonlinearity of damping-associated material hysteresis and friction. To overcome the aforementioned problems in deterministic approaches, stochastic approaches have been proposed by several authors [3,4]. They performed FE model updating by considering the scatter of all physical parameters through optimization with Monte Carlo simulation. However, considering current computing power, such approach is still complex and much more computationally expensive than the deterministic approaches, its application for large-scale structures such as entire aircraft and spacecraft may be limited.

From a historical viewpoint, at an early stage of FE model updating, most researchers simply concentrated on tuning eigenfrequencies and mode shapes to test results. By the same token, in many military and space standards [5–7], error criteria are still only based on the accuracy of eigenfrequencies and mode shapes. Furthermore, to find out transient response or frequency response from FE models, the modal damping ratio is typically obtained experimentally for dominant modes showing significant response, but the modes whose damping cannot be measured adopt 1–2% low modal damping around for conservative prediction as a rule of thumb although several remedies have been reported to consider the uncertainty [8,9].

During the design and analysis of complex aircraft and spacecraft, many engineers have focused on developing accurate mathematical models having strong correlation with test results [10–12]

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in terms of not only eigenfrequencies and mode shapes but also frequency response function (FRF) including damping effect. It is extremely important for the safety of pilots and passengers, and evaluating the dimensional stability of high-resolution optical payloads, which is hard to predict by ground test facilities and instruments [13–16].

To increase the FRF similarity, several novel approaches have been proposed with sensitivity analysis considering the effect on FRF deviation with various damping models such as proportional viscous and structural damping. As in Lin's work [17], it simultaneously updates both the stiffness and damping matrices to minimize the FRF error iteratively. On the other hand, sequential updating approaches [18–20], also termed two-step approaches, have been proposed. In the first step, the mass and stiffness matrices are updated with test data iteratively, which is the same with the conventional iterative method. In the second step, the damping matrix is updated with the mass and stiffness matrices obtained in the previous step by solving the governing equation again to maximize the similarity between analysis and test in terms of FRFs.

However, from a practical viewpoint, some points still must be improved due to the limitations of the iterative methods. One major weakness is that users have to identify the parameters affecting modal properties and continuously update the FE model until the errors in the modal properties are reduced to be within the predefined tolerance limit. In the case of eigenfrequencies, 3–5% deviation is considered normal in many military aerospace standards as summarized in Table 1. However, when the coupling effect between the system and input source is quite critical, such deviation should be reconsidered to minimize the error in dynamic response. Moreover, in a complex system comprising many components, identifying the parameter is not always straightforward. Therefore, some modes cannot be well matched to the test values because the quality of model updating is determined by a tradeoff between time and accuracy.

In the case of modal damping, it is possible to identify the modal damping ratio by the half-power method or the logarithmic decrement for significant modes of the vibration test results. However, in general, there are more modes in the FE model than those in the test results, especially for large aircraft and spacecraft FE model having a high modal density (number of modes per frequency) due to heavy launch weight. If we set the modal damping ratio conservatively for the unmeasured modes, it works as a source of discrepancy between test and analysis for the FRF.

The main objective of this work is to propose a post-processing scheme in the framework of semi-direct model updating that eliminates eigenfrequency error and refines modal damping ratios for unmeasured modes, which thus leads to FRFs more improved. To the authors' best knowledge, this has never mentioned in other research papers, but is really important to structural dynamics engineers. By applying this scheme to the iteratively-updated model, we significantly improve the accuracy of frequency response function through eigenfrequency elimination and refining modal damping ratios for unmeasured modes.

The proposed scheme comprises three model updating procedure steps. First, to match analysis results with test results, the FE model is updated by the conventional iterative model updating within the tolerance limit. Second, to enhance the reliability of the FRFs, marginal eigenfrequency deviation around 3–5% between test and analysis is replaced by measured ones without changing the corresponding eigenvectors. Furthermore, the stiffness matrix is recalculated using the direct updating method: the matrix-mixing approach iteratively with the mass matrix preserved. Finally, the unmeasured modal damping ratios are obtained by minimizing FRF error. Hence, FRFs obtained by the proposed scheme show excellent agreement with test data.

The remainder of this paper is organized as follows. In Section 2, the theoretical background of the proposed work is briefly summarized. Then, in Section 3, two practical examples, including a 9-degrees of freedom (DOF) mass-spring structure and a complex satellite FE model, are treated to demonstrate the efficiency and accuracy of the proposed work. Finally, we close the paper with concluding remarks in Section 4.

2. Theoretical background

2.1. Iterative FE model updating for structural dynamics and assessment of the similarity of frequency response functions

For a displacement of kth output DOF subjected to a unit force of lth input DOF, structural response, termed a receptance element $\alpha_{kl}(\omega)$, is defined as

$$\alpha_{kl}(\omega) = \frac{u_k(\omega)}{F_l(\omega)} \cong \sum_{r=1}^{N_{eig}} \frac{(\boldsymbol{\varphi}_r)_k(\boldsymbol{\varphi}_r)_l}{\omega_r^2 - \omega^2 + 2j\omega\omega_r\xi_r}, \tag{1}$$

where $(\boldsymbol{\varphi}_r)_l$ indicates the lth component of the rth mass normalized eigenvector of the system; N_{eig} is the number of eigenmodes in the frequency range of interest, and ξ_r is the modal damping ratio at the corresponding mode r. ω is the frequency of the excitation force, and j is an imaginary number ($j^2 = -1$).

During iterative model updating [2], the sensitivity matrix $\mathbf{S}$ is computed on the target response R_i with respect to parameter p_j. Especially, when the eigenfrequency f_i (Hz) is taken as a target response, the sensitivity component S_{ij} by the first-order difference can be expressed simply as

$$S_{ij} = \frac{\partial R_i}{\partial p_j} = \frac{\partial f_i}{\partial p_j} \approx \frac{\Delta f_i}{\Delta p_j} = \frac{\boldsymbol{\varphi}_i^T(\frac{\Delta\mathbf{K}}{\Delta p_j} - 4\pi^2 f_i^2 \frac{\Delta\mathbf{M}}{\Delta p_j})\boldsymbol{\varphi}_i}{8\pi^2 f_i(\boldsymbol{\varphi}_i^T\Delta\mathbf{M}\boldsymbol{\varphi}_i)},$$
$$\text{with } \mathbf{K} = \int_\Omega \mathbf{B}^T\mathbf{D}\mathbf{B}d\Omega \text{ and } \mathbf{M} = \int_\Omega \rho\mathbf{N}^T\mathbf{N}d\Omega, \tag{2}$$

where subscript i is the index of each mode, $\boldsymbol{\varphi}_i$ is the mode shape vector of ith mode, Δ denotes the increment, and ρ is structural density. $\mathbf{B}$ and $\mathbf{N}$ are strain-displacement and displacement interpolation matrices, respectively, and $\mathbf{D}$ is stress–strain matrix of the material. Here, f_i and p_j are the eigenfrequency and the structural parameter such as elastic modulus, thickness and so forth, respectively. The sensitivity about mode shapes and FRFs can be found in the literature [2] and already available in the commercial software such as FEMtools [21]. This model updating is continued until the predefined tolerance is satisfied as seen in the flow chart (see Fig. 1).

To assess the similarity of eigenfrequencies and mode shapes between test and analysis, the following quality indexes: eigenfrequency error and modal assurance criteria (MAC) have been widely used as

$$\frac{\Delta f_i}{f_i^t} = \frac{f_i^t - f_i^a}{f_i^t}(\%), \tag{3}$$

$$MAC(i,j) = \frac{|\boldsymbol{\varphi}(f_i)^t \cdot \boldsymbol{\varphi}(f_j)^a|}{|\boldsymbol{\varphi}(f_i)^t||\boldsymbol{\varphi}(f_j)^a|}, \tag{4}$$

in which superscripts t and a denote test and analytical results.

Besides this, frequency domain assurance criterion (FDAC) that evaluates the similarity of FRFs at the specified eigenfrequencies, and frequency response assurance criterion (FRAC) that finds the correlation of the paired FRFs over entire frequency range [22], are expressed as