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A model-updating approach based on the component mode synthesis method and perturbation analysis

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A B S T R A C T

A model-updating approach based on an improved free-interface component mode synthesis method is proposed. First, the equivalent higher-order matrix of the system is developed using a set of linearly independent vectors to capture the effects of the neglected higher-order modes. Second, the perturbation method is applied to derive the change for both eigenvalues and eigenvectors of each component while implementing a modification to the updated finite element model. The perturbation for both the eigenvalues and eigenvectors of each component are used to formulate the synthesis equations containing the perturbation expression. Next, the model-updating process is conducted using the synthesis model for which the degrees of freedom have been greatly reduced. The reduction in the total degree of freedom speeds up the solution process for the model-updating problem. Finally, the computational efficiency and accuracy of the presented method is demonstrated using a wing structure and by modal testing of a bolted plate.

1. Introduction

The finite element (FE) model-updating technique is an effective method to improve the prediction accuracy of a model. Over the past decades, the model-updating technique has been developed in a large number of fields, such as damage detection [1], structural health monitoring [2] and structural response prediction. The technique of updating via structural design parameters is increasingly widely used because the physical meaning of the design parameters can be reflected and because the characteristics of system matrices can be preserved during the process of model updating.

Most model-updating problems, which are based on structural parameters, can be formulated as a multi-objective optimization problem, and the design parameters and sensitivity matrices of the analytical model must be computed in each iteration. Nevertheless, with the development of industry technology, mechanical structures are becoming increasingly complex, and the scale of models is extensive. For the FE models involving thousands or even millions of degrees of freedom (DOFs), the calculation cost using the traditional updating approach is high, even prohibitively so. Therefore, some researchers have employed surrogate model technology, which has been strongly emphasized in optimization design and reliability analysis, instead of the finite element method (FEM) in the model-updating process. The results of relevant studies

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prove that the surrogate model technology can improve the computational efficiency of complex models. The response surface methodology (RSM) has been widely employed in optimization problems because of its efficiency and simplicity [3]. He et al. [4,5] applied a surrogate model of the radial basis function (RBF) to the FE model-updating problem to improve its calculation efficiency.

The surrogate model technique based on the model-updating method is limited because it inevitably introduces errors during construction of the surrogate model. Small perturbations can produce deviations between the results obtained using the modified model and those obtained using the real model. The effect of model updating is largely dependent on the accuracy of the surrogate model. Many factors influence the accuracy of the surrogate model, and the modeling process relies strongly on the personal experiences of the researcher; as a result, there is still no unified modeling standard for reference. This lack of a modeling standard greatly limits the application of this method.

For the above reasons, many scholars have sought other efficient model-updating methods. The component mode synthesis (CMS) technique, which can significantly reduce the model size, has been widely applied in the dynamic analysis of structures. The early CMS technique was established to reduce the DOFs of the linear vibration system [6–8]. Recently, with the emergence of various new structures, the CMS methods have been applied to more sophisticated problems. Mencik et al. developed a wave finite element (WFE) and CMS method to investigate the frequency behavior and wave transmission coefficients of junctions [9,10]. To improve the calculation efficiency, the Craig–Bampton CMS method has been employed to analyze elastic multibody systems [11,12]. Kawamura and Naito [13] applied the CMS method to the study of nonlinear forced vibration of a multi-degree-of-freedom system and found that the method presented is effective when the components do not include rigid modes. Improved free-interface CMS methods have been presented for viscoelastically damped systems [14,15]. E. Roibás Millán et al. [16] proposed a hybrid method within the CMS framework for the dynamic response analysis of complex systems across a broad frequency range. He et al. [17] presented a new free-interface CMS approach for a localized nonlinear system using hybrid coordinates. Klaus-Jürgen Bathe and Jian Dong [18] used subspace iterations to improve the computational accuracy of CMS. Duc-Minh Tran [19] combined CMS with multi-stage cyclic symmetry reduction to analyze multi-stage cyclic structures. An example of bladed-disk assemblies was presented to illustrate the efficiency of the proposed method. To decrease the numerical size of a dynamic mixed displacement-stress FEM, five different sub-structuring and CMS reduction methods were adapted by Pierre Garambois [20], and the reduction effects of various methods were contrasted. A. Heinlein [21] proposed a parallel implementation of the approximate CMS and discussed the parallel scalability issues. G. Masson [22] proposed a new method that incorporated the Craig–Bampton method to enrich the standard super-element reduction methods and improve the efficiency of the optimization process.

For the model-updating problems, Qingguo Fei et al. [23] proposed a model-updating method that adopts the response function. Shun Weng [24,25] proposed a substructure-based FE model-updating technique. Jie-xin Yu [26] proposed an element-by-element model-updating method based on the CMS method for large-scale structures. The eigensensitivities of each component are assembled into the eigensensitivity of the global structure. Costas Papadimitriou [27] presented a framework based on the Craig–Bampton CMS method for deterministic and Bayesian FE model updating and found that the method applied in the present study can efficiently reduce the time consumption in the reanalysis of large-order models.

Existing methods that combine the constraint interface CMS with the model-updating technique can efficiently reduce the associated time consumption. However, the major limitation of the methods using constraint modes is the inability to easily obtain the experimental data for the model-updating process. It is much more convenient to conduct modal test for the free-free structures than to those with extra constraints, which means that using modes of the free-free structure will benefit the whole model-updating process. As for this reason, the free-interface CMS is the better choice for model-updating. In this study, an improved free-interface CMS is proposed that is integrated into existing FE model-updating formulations to reduce the computational burden involved in reanalysis. In addition, the complete dynamic system is divided into several components, and the components that include updating parameters are analyzed using the small-parameter-perturbation method. Next, the interface compatibility conditions are applied to combine all of the equations to provide the synthesis equations. The model-updating problem is formulated as a multi-objective optimization problem, and iterative calculation is performed for the reduced system synthesis equations. The perturbation method is applied with the CMS; i.e., one does not need to solve the eigenvalue problem of the synthesis equations at each iteration while conducting the model-updating process. Generally, reanalysis is always required when performing the optimization process at each iteration, while solving the eigenvalue problem during the reanalysis process consumes the highest time cost of the total CPU time for the model-updating; with the combination of the CMS and perturbation method, the synthesis equations can be constructed easily without solving the eigenvalue problem of the synthesis model at each iteration while doing performing the optimization process, thereby reducing the time consumed at each model-updating iteration. In addition, the individual components are analyzed independently, and this capability is valuable for the case in which part of the model must be updated or validated since only those parts are reanalyzed during model updating, while the rest of the model remains unchanged. This approach is a relatively efficient way to update the model. Finally, validation of the proposed method is demonstrated through model updating of a metallic wing box.

2. Perturbation analysis of components

The system can generally be separated into several parts. For arbitrary components of the structure, the equation of the motion can be expressed as