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Dynamic model updating based on strain mode shape and natural frequency using hybrid pattern search technique

Ning Guo [a], Zhichun Yang [a, *], Le Wang [a, **], Yan Ouyang [a], Xinping Zhang [b]

[a] Northwestern Polytechnical University, Xi'an 710072, China
[b] AVIC Shaanxi Aircraft Industry (Group) Corporation LTD, Hanzhong 723000, China

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A B S T R A C T

Aiming at providing a precise dynamic structural finite element (FE) model for dynamic strength evaluation in addition to dynamic analysis. A dynamic FE model updating method is presented to correct the uncertain parameters of the FE model of a structure using strain mode shapes and natural frequencies. The strain mode shape, which is sensitive to local changes in structure, is used instead of the displacement mode for enhancing model updating. The coordinate strain modal assurance criterion is developed to evaluate the correlation level at each coordinate over the experimental and the analytical strain mode shapes. Moreover, the natural frequencies which provide the global information of the structure are used to guarantee the accuracy of modal properties of the global model. Then, the weighted summation of the natural frequency residual and the coordinate strain modal assurance criterion residual is used as the objective function in the proposed dynamic FE model updating procedure. The hybrid genetic/pattern-search optimization algorithm is adopted to perform the dynamic FE model updating procedure. Numerical simulation and model updating experiment for a clamped-clamped beam are performed to validate the feasibility and effectiveness of the present method. The results show that the proposed method can be used to update the uncertain parameters with good robustness. And the updated dynamic FE model of the beam structure, which can correctly predict both the natural frequencies and the local dynamic strains, is reliable for the following dynamic analysis and dynamic strength evaluation.

1. Introduction

It is well known that the reasonable dynamic finite element (FE) model of a structure is the prerequisite for performing accurate structural dynamic analysis. However, the modeling accuracy of the dynamic FE model relies mainly on the professional skill and work experience of researchers. Generally, it is very difficult to directly build a high-precision dynamic FE model that can represent the actual structure perfectly in the structural dynamic analysis. Thus, how to obtain a high-precision dynamic FE model of a structure is the key point in the dynamic analysis. The idea of dynamic FE model updating, which combines the finite element modeling with the experimental measurements, is proposed to solve this problem. Firstly, according to the actual conditions of the structure, a priori dynamic FE model is built. Then the measured data from

* Corresponding author. Tel./fax: +86 029 88460461.
** Corresponding author.
E-mail addresses: yangzc@nwpu.edu.cn (Z. Yang), le.wang@nwpu.edu.cn (L. Wang).

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dynamic testing, which can reflect the dynamic characteristics of the structure, is used to update the established dynamic FE model. The analytical results of the updated dynamic FE model must be in agreement with the corresponding measured data in the concerned frequency band.

Basically, the model updating methods may be classified into two major groups, i.e., the direct updating methods and the iterative updating methods. The former one based on the matrix operation or the least square method can be used to compute the changes in the mass and/or stiffness matrix directly. This updating method is efficient, but the updated results cannot be interpreted by physical sense in most cases [1]. Moreover, the symmetry and sparsity of the original mass and stiffness matrix may be lost after updating [2]. In contrast, the iterative updating method by imposing proper constraints can ensure the updated results with physical meaning and high accuracy. The iterative updating method usually uses the sensitivity analysis to formulate the iteration relation [4–6]. The primary issue of the iterative updating method is how to compute the sensitivity of the objective function with respect to updating parameters efficiently. Meanwhile, for updating problems with a large number of parameters or parameters with different dimensions, the key point is how to determine the updating parameters which are efficient for dynamic FE model updating. It is found that combination of the variables with different dimensions in one group may deteriorate the convergence in the updating process and generate ill-conditioned problems due to their couplings [7].

To establish a reasonable objective function is also an important step in a dynamic FE model updating procedure. The objective function, which indicates the discrepancies between the actual structure and the corresponding dynamic FE model, is normally formulated using the residuals between the experimental and the analytical datum. The modal parameters related function, including natural frequency and mode shape, is commonly used to form the objective function in the dynamic FE model updating. For natural frequency, the absolute or the relative errors between the experimental and the analytical frequencies can be directly used as the objective function for dynamic FE model updating. For mode shape, the modal assurance criterion (MAC) [8] between the experimental and the analytical mode shapes is defined firstly. Then, the residuals of MAC value are adopted to develop the objective function. However, if the natural frequency or mode shape is used alone to formulate the objective function, some useful structural information may be neglected. Thus, natural frequencies and mode shapes are usually combined to establish the objective function. Two common approaches are utilized: in the first approach, the weighted summation of natural frequency error and mode shape residual is adopted to formulate the objective function [3,9]; and in the second approach, natural frequency error and the mode shape residual, are simultaneously considered in dynamic FE model updating by using multi-objective optimization technique. The second approach can overcome the difficulty of weighting the individual objective function in the first approach [10].

It is well known that the natural frequencies can be accurately identified, while mode shapes cannot be identify accurately. As a result, it may reduce the accuracy of the updated model by using the inaccurate measured mode shapes. To solve this problem, Meruane [11] proposed a model updating method that uses the anti-resonant frequencies identified from transmissibility measurements instead of mode shapes. Moreover, other feature parameters defined by mode shapes, except for MAC, are used to establish the various objective functions, e.g. the modal strain energy [12] defined by mode shape and the stiffness matrix of the structure, the modal flexibility matrix [13] formed by the measured natural frequencies and mode shapes.

Strain mode shape, as a generalized modal parameter, has great potential for dynamic model updating applications because it is sensitive to local changes in the structure, such as local changes in geometrical, physical and mechanical parameters [14]. However, to the best of author's knowledge, few publications deal with model updating methods using the strain mode shape. In the current work, we use the strain mode shape and the hybrid pattern search optimization technique to enhance the performance of model updating. The coordinate strain modal assurance criterion (COSMAC) extension to MAC is developed to evaluate the difference between the actual structure and the corresponding dynamic FE model. Moreover, in order to overcome the difficulties in updating dynamic FE models by aforementioned direct or iterative updating method, the hybrid pattern search (HPS) optimization technique, which synthetizes the advantages of pattern search (PS) optimization technique and genetic algorithm (GA), is introduced to solve the dynamic FE model updating problem. Finally, the proposed method is validated by the updating of a beam structure numerically and experimentally.

2. Model updating using strain mode shapes and natural frequencies

2.1. Strain mode analysis and coordinate strain modal assurance criterion

The equations of motion for a forced vibration system having N degrees of freedom can be expressed as,

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f} \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K} \in \mathbb{R}^{N\times N}$ are the mass, damping and stiffness matrix, respectively, $\ddot{\mathbf{x}}$, $\dot{\mathbf{x}}$ and $\mathbf{x}$ are the vectors of acceleration, velocity and displacement response, respectively, f is the force vector.

The natural frequencies $\boldsymbol{\omega} = [\omega_1, \cdots, \omega_n]$ and mode shapes $\boldsymbol{\varphi} = [\boldsymbol{\varphi}_1, \cdots, \boldsymbol{\varphi}_n]$ of the first n modes can be obtained by the solution of the eigenvalue problem according to Eq. (1). It is known that the mode shape indicates the displacement vector of vibration system in the modal coordinate. According to the relationship between displacement and strain, the strain mode shape can be obtained by