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A model updating method considering the complex mechanical environment

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ABSTRACT

As the accuracy and stability requirements of space structures increase, structural microvibration has become a critical problem. However the measurement of the in-obit microvibration is difficult and costly compared to the measurement on the ground. It's essential to establish the relationship between the ground test data and in-obit microvibration. In this paper, a model updating method is established to predict the in-orbit microvibration model using the ground test data. A numerical example of a satellite model is presented to validate the model updating method.

Introduction

As structural microvibration requirements are becoming more and more severe to ensure the accuracy and stability demands for the sensitive payloads, it is essential to investigate the characteristics of microvibration both theoretically and experimentally. However the measurement of the in-orbit microvibration is difficult and costly. The microvibration measurement is more convenient to be implemented on the ground, whereas there are obvious differences between the ground and the in-orbit mechanical environment, which will lead to different microvibration characteristics. Consequently it is very important to propose a method to transform the ground microvibration test model to the actual in-orbit model.

The vibroacoustic effect cannot be ignored in the ground microvibration test. However most of the model updating methods focus on the structural model updating [1,2]. The issue of model updating for vibroacoustic systems has not been addressed much. Model updating through an iterative approach has been conducted to study the vibroacoustic characteristics of a cavity [3]. An updating method for 2D acoustic models based on the constitutive relation error method was proposed by Decouvreur et al. [4]. This method was extended to the updating of 3D acoustic finite element models in the literature [5] and the identification of admittance coefficient of sound absorbing materials [6]. Dhandole et al. [7] considered the updating of the acoustic finite element models by using the sequential quadratic programming method. Modak [8] developed a direct matrix updating formulation for vibroacoustic finite element models which preserves the symmetry of the mass and stiffness matrix. Based on the complex acoustic frequency response function, Wan [9] proposed a new approach for updating the acoustic finite element model.

The above updating methods are all applied to vibroacoustic systems, whereas, besides the air effect, the influence of gravity and free-free configuration should also be taken into account. These factors affect the microvibration characteristics of the space structures on the ground. In this paper, a model updating method considering all the above mechanical environment factors (air, free-free configuration and gravity) is established based on the ground test data. A more accurate in-orbit model can be obtained by removing the above mechanical environment factors from the updated acoustic finite element model on the ground.

Mechanical environment simulation

Free-free configuration

In the ground microvibration test, the space structures are suspended by straps. This free-free configuration on the ground can achieve small constraint frequency, but the constraint frequency cannot be zero as in orbit, which will also induce the microvibration characteristics differences. In order to take the free-free configuration effect into account, the straps' mass and stiffness matrix are added to the initial finite element model.

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Gravity

A pre-stress analysis is carried out to calculate the effect of gravity. The mass matrix is the same as that without gravity. However the stiffness matrix, which comprises two parts, is different. The first part is the stiffness matrix without gravity. The second part is the added stiffness matrix induced by the pre-stress effect.

Air

The influence of air on the ground test model is very important especially when the modal frequency is relatively low. It is assumed that air is incompressible and inviscid. The influence of air can be transformed into the added air mass matrix. The acoustic boundary element method is adopted as in the literature [10]. The elements in the literature [10] are all triangular elements. However, it is not convenient to share the acoustic and structure finite element partition when most of the structure elements adopt quad elements and few are triangular elements. In this paper, the method in the literature [10] is expanded to the combination of triangular and quad elements so that the acoustic and structure model can share the mesh partition. Replace Eq. (18) in the literature [10] by

$$A_{PQ} = \sum_{k=1}^{n} A_{\gamma_k} \tag{1}$$

where n is the number of element edges, A_{γ_k} is the curvilinear integral on the edge γ_k, A_{PQ} is the influence coefficient between the point P and Q.

Model updating method

In this paper, a model updating method considering the ground test mechanical environment including air, free-free configuration and gravity is established. The objective function is the sum of squares of the modal frequencies differences between the test data and the acoustic finite element calculation. The model updating method is described as follows:

$$\left.\begin{array}{l} \min\ J(x) = \sum_{j=1}^{n} W_j \left(\frac{f_j^{\exp} - f_j}{f_j^{\exp}}\right)^2 \\ \text{s.t. } x_i^l \leqslant x_i \leqslant x_i^u i = 1, 2, \cdots m \end{array}\right\} \tag{2}$$

where n is the order of the modal that participates in the model updating, W_j is the weighted coefficient for the jth modal, f_j^{exp} is the jth test modal frequency, f_j is the jth calculated modal frequency, x_i is the $i\ th$ parameter that participates in the model updating, x_i^l and x_i^u represent the $i\ th$ parameter's lower and upper bounds respectively, m is the number of parameters that participate in the model updating.

The acoustic finite element model considering the ground mechanical environment is established in the first step of the proposed model updating method. The flow chart is shown in Fig. 1. Firstly the initial finite element model is established, and then the free-free configuration and gravity field are added. Based on the pre-stress analysis, the model's mass and stiffness matrix can be obtained. The improved boundary element method in Section "Gravity" is employed to calculate the added air mass matrix. The model considering the ground mechanical environment is finally obtained by adding the added air mass matrix.

The procedure of the model updating method is shown in Fig. 2. It can be described as follows,

(1) Establish the model considering the ground complex mechanical environment;

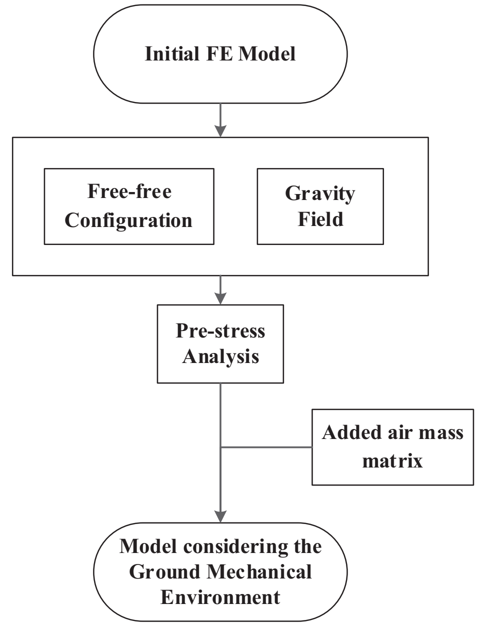

Fig. 1. Flow chart of building the model considering the ground mechanical environment.

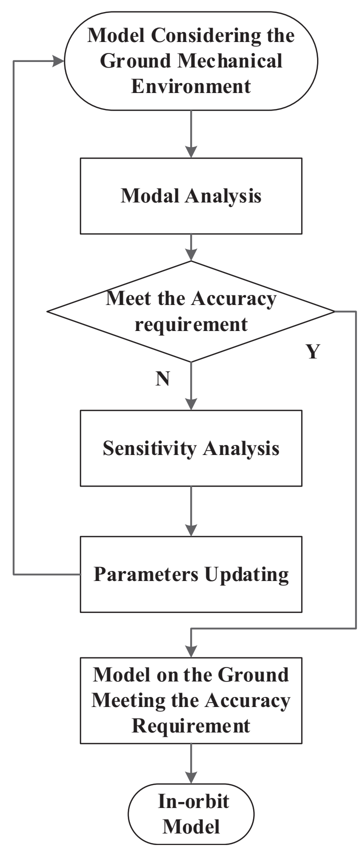

Fig. 2. Flow chart of the model updating method.

(2) Conduct the modal analysis of the model;

(3) If the objective function meets the accuracy requirement, turn to step (4), or else carry out the sensitivity analysis. Based on the sensitivities, the updated parameters can be obtained, and then return to step (1). Based on the updated parameters, the new acoustic finite element model is established;

(4) Remove the mass and stiffness matrix induced by air, free-free configuration and gravity, and the in-orbit model is obtained.

Numerical example

In this section, an example of a simplified satellite model is presented. The improved boundary element method in Section "Gravity" is validated using the rectangular cantilever plate in the literature [11]. The first 4 frequencies of the plate in the literature [11] are 6.00 Hz, 33.10 Hz, 40.10 Hz and 112.60 Hz respectively. Using the improved boundary element method, the first 4 order frequencies are 6.07 Hz, 32.36 Hz, 40.60 Hz and 109.10 Hz respectively. The relative errors of frequencies are 1.17%, 2.24%, 1.25% and 3.11% respectively. This proves that the improved boundary element method is fairly good in estimating the effect of air. An acoustic finite element model of the ground test considering the ground mechanical environment is built, which is shown in Fig. 3. The effect of air is transformed into the node mass as the triangles at nodes in Fig. 3.

The objective function is chosen as the sum of the relative square errors of the first 10 frequencies differences between the test data and the acoustic finite element calculation. Three variables, which are sensitive to the frequencies, are selected as the updating parameters: the elastic modulus of the inner beams E1, the equivalent elastic modulus of the honeycomb sandwich plate E2, and the thickness of the honeycomb sandwich plate. The convergence curve of the objective function is shown in Fig. 4. The iteration of the parameters is shown in Fig. 5. The iteration curve of the first 3 order frequencies is shown in Fig. 6. After 5 iterations, the procedure converges, the updated model considering the ground mechanical environment is obtained. Remove the mass matrix and stiffness matrix induced by air, free-free configuration and gravity, the in-orbit model is obtained.

The Modal Assurance Criterion (MAC) [12] value is used to validate the consistency of modal shape between the test model and the updated model. The MAC is defined as follows:

$$\mathrm{MAC} = \frac{(\psi_1^H \psi_2)^2}{\psi_1^H \psi_1 \psi_2^H \psi_2} \tag{3}$$

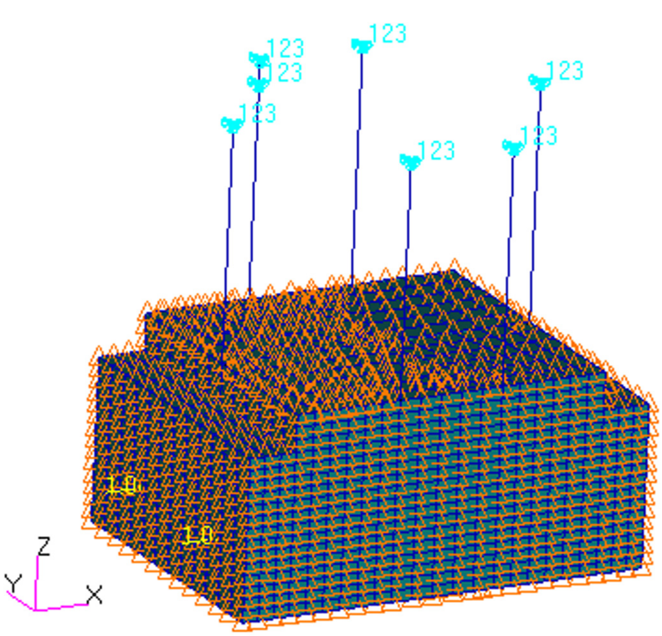

Fig. 3. Finite element model of the ground test.

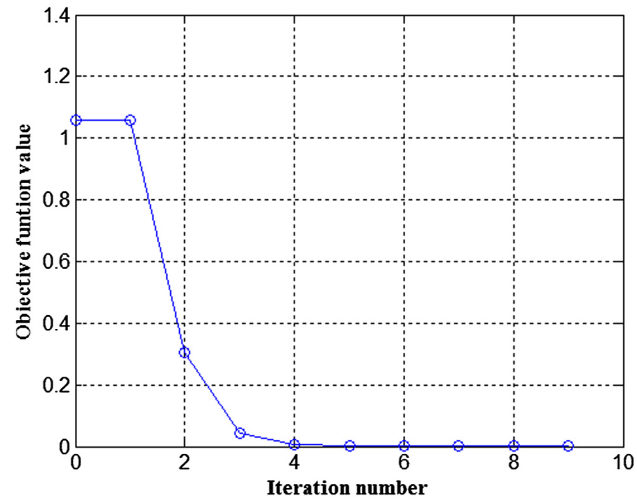

Fig. 4. The convergence curve of the objective function.

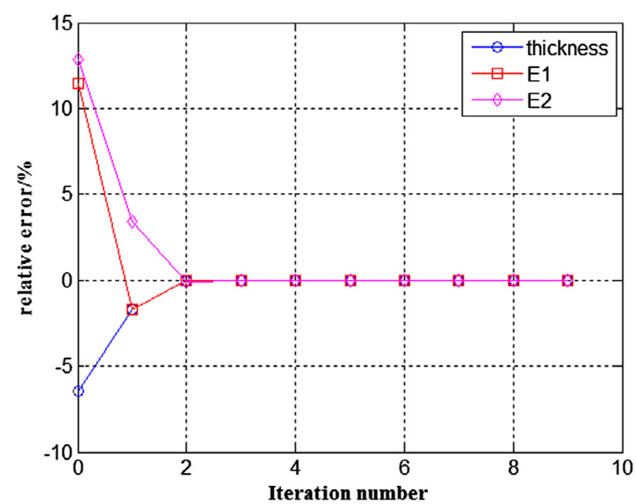

Fig. 5. The iteration curve of the updating parameters.

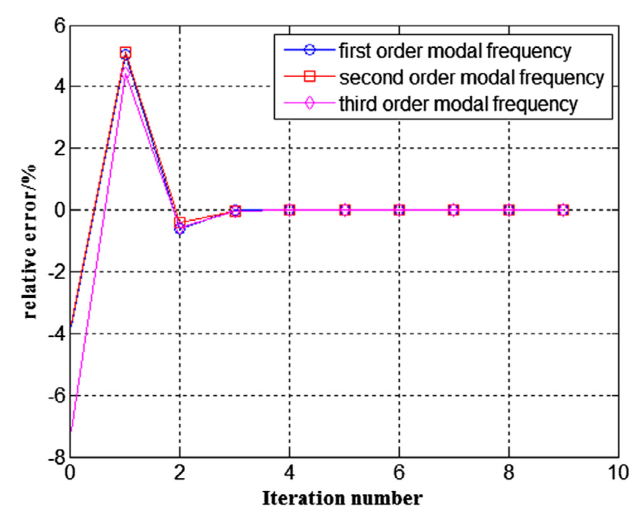

Fig. 6. The iteration curve of the first 3 order frequencies.

Table 1
The MAC values of the test modal shapes and the updated finite element modal shapes.

Modal order	1	2	3	4	5	6	7	8	9	10
MAC value	0.997	0.989	0.986	1.000	1.000	1.000	1.000	1.000	1.000	1.000

where ψ_1,ψ_1 are the two vectors representing the modal shapes of the updated model and the test model. If they are in the same direction, the value of MAC is 1. The better the consistency is, the larger the value of MAC is. The MAC values between the updated modal shapes and the test modal shapes are shown in Table 1. The smallest value of MAC is 0.986 which shows good consistency of modal shapes between the updated model and the test model.

Conclusions

In this paper, a model updating method considering the complex mechanical environment is proposed. The method is the combination of the structural finite element method, acoustic boundary element method and the sensitivity analysis method, which is practical in engineering. As the influence of air, free-free configuration and gravity are considered in this method, a more accurate in-orbit model could be obtained for the microvibration analysis.

The proposed method can be extended to other problems which is difficult to test in a single mechanical environment. Based on the test data in a convenient environment and the proposed model updating method, the mechanical characteristics in the other environment can be obtained.

Acknowledgements

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