Modal Analysis for Trailing Edge of Morphing Wing of Composite Material

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Abstract: Based on the handmade of trailing edge of morphing wing and flexible composite skin, this paper develops modal analysis both on finite element models in PATRAN and MSC.NASTRAN and experiment. The results show that the deviation of the first-four natural frequencies from the finite element software results is within 10% and the natural modes are basically the same, which provides the effectiveness of the finite element analysis method. Through the vibration modal analysis experiment of the trailing edge, the first-order natural frequency of the structure is obtained as 13.08Hz, which provides useful data for the subsequent study of strain characteristics.

1. Introduction
A large number of scholars have studied the morphing wing and made a great deal of achievements. H.P. Monner[1] proposed a concept of flexible ribs for adaptive wing, whose lower and upper skins are both flexed by active ribs, the camber variation is achieved with a smooth contour and no additional gaps; S. Ricci[2] manufactured a wing box model which can achieve both a spanwise and a chordwise differential camber variation based on this concept of flexible ribs; thus, Yang Zhichun[3] came up with a design method for rotating rib structure aiming at flexible deflection track of trailing edges based on curve approximation theory.

Morphing wing can greatly improve the flight control ability, reduce aerodynamic resistance and lighten the structural weight as well as improve the characteristics of wing flutter and the ability of resistance against gust in order to enhance maneuvering characteristics of aircrafts.[4] And then, flexible skin with smooth and continuous large deformation has become the focus of research. In this paper, the modal simulation analysis based on PATRAN and experimental testing are applied to the composite flexible skin of the trailing edge of morphing wing, which provides effective reference data for subsequent strain experiments.

2. Modal Theory Analysis
The basic equations of natural vibration of structure[5]:

\[ [M] \ddot{x} + [K] \dot{x} = \theta \]

where \([M]\) is the mass matrix, \([K]\) is the stiffness matrix, \([x]\) is the displacement vector.
Suppose the system to do simple harmonic motion, then \([x] = (\Phi) \sin(\omega t + \psi)\), The above formula (1)
can be transformed into:
\[
([K] - \omega^2[M])\{\varphi\} = 0
\]  
(2)

By solving the above characteristic equation, the intrinsic modal parameters for each order of the structure is obtained.

3. Finite Element Analysis based on MSC.NASTRAN

Due to the complex structure of the trailing edge of the morphing wing, it is difficult to model for the integral structure, therefore, the finite element modeling and analysis for the flexible composite skin of morphing wing trailing edge are carried out to obtain the inherent characteristics of the skin, which lays the foundation for the analysis of inherent characteristics of the morphing wing.

Vibration modal analysis of the flexible composite skin is performed using MSC.NASTRAN solution sequence SOL13, and the process of modeling on PATRAN[6][7] is: ① Create critical points and lines to draw the cross-section of the skin to complete the geometric model of the composite flexible skin; ② Select the appropriate cell to grind according to the finite element theory; ③ The material properties of the flexible skin are defined as reinforced fiberglass materials with an elastic modulus of 21GPa, a Poisson's ratio of 0.3 and a density of 1.2 g/cm³; ④ Define the boundary conditions as flexible skin fixed at one end and a free state in the other end, just the same condition as the vibration experiment; ⑤ Select the analysis mode as the general modal analysis, and choose NORMAL MODES in Patran analysis module.

![Figure 1](attachment:image1.png)

(a) First order mode of vibration  (b) Second order mode of vibration

![Figure 1](attachment:image2.png)

(c) Third order mode of vibration  (d) Fourth order mode of vibration

Figure 1 1st to 4th Vibration Modes of Flexible Composite Skin

Then 1st to 4th vibration modes of flexible composite skin are obtained by MSC.NASTRAN, and the first four orders natural frequencies of the flexible wing skin simulation analysis are 4.99Hz, 18.48Hz, 28.74Hz and 40.37Hz.

4. Flexible Skin Specimen of Composite Material

The finite element software PATRAN and NASTRAN are used to establish the model of flexible skin and simulate its longitudinal deformation capacity and transverse load carrying capacity, so as to optimize the lay-up thickness and the radius of the U-shaped flexible skin. In order to simplify the finite element model and its solution process, it is assumed that each layer of fiberglass reinforcement is isotropic. Based on the comprehensive consideration of the simulation results, the mold making and the skin preparation process, the size of the U-type flexible skin is determined: R (the radius of U-type skin) is 4mm, d (the thickness of the lay-up) is 1.2mm and h (straight section length of U-type) is 2mm,
shown in Figure 2. The comprehensive mechanical property both longitudinal deformability and lateral load capacity of the flexible skin are optimization in this size.

NACA0012 airfoil is selected as the prototype of the trailing edge structure of morphing wing, and the rib is designed as a trailing edge with three sections of articulation, shown as figure 3. The material of the ribs and stringers of the trailing edge structure is epoxy board, and the ribs are hinged together by three joint segments with the U-type flexible skin of glass fiber reinforced material.

5. Modal Experiment of Composite Flexible Skin
The click pick-up method is used in this vibration mode analysis experiment, and the response is got by the accelerometer while hitting the test points sequentially with force-hammer. The instruments used in this experiment includes a hammer (086C03 of PCB), dynamic signal analyzer (SignalCalc Quattro of DP), accelerometer(352C68 of PCB) and one personal computer equipped with ICATS modal analysis software developed by the London Institute of Technology. The experimental setup is shown as figure 4.
frequency response data into ICATS; multi modal polynomial fitting method is selected for modal parameter identification; the order of the modal matrix is set to 32; the analysis frequency range is set to 1Hz~100Hz; the main vibration mode is chosen as MCF (Modal Confidence Factor) closest to 1. The orthogonality between the modes of each order is verified by calculating the MAC (Modal Assurance Criteria) value in parameter identification, which can evaluate the modal model. When the MAC value is close to 0, it shows that the mutual independence of the two order modes is higher; when the MAC value is close to 1, it shows that the degree of coupling between the two order modes is higher. The natural frequency of ICATS software parameter identification is shown in table 1, and ICATS modal parameter identification results shown in table 2, vibration patterns are shown in figure 5.

| Orders | Natural frequency (Hz) | Natural frequency (Hz) |
|--------|------------------------|------------------------|
|        | U-type flexible skin    | The trailing Edge with flexible skin |
| 1      | 4.98                   | 13.08                   |
| 2      | 18.74                  |                         |
| 3      | 24.57                  |                         |
| 4      | 43.31                  |                         |

| Orders | Finite Calculating | Experimental Results | Deviation(%) |
|--------|--------------------|----------------------|--------------|
| 1      | 4.99               | 4.98                 | 0.2          |
| 2      | 18.48              | 18.73                | 1.3          |
| 3      | 28.74              | 27.52                | 4.2          |
| 4      | 40.37              | 43.31                | 7.3          |

Figure 5 First to Fourth Vibration Patterns of Flexible Skin of Trailing Edge

Table 1 shows that the 1-4 order natural frequencies of the trailing edge of a morphing wing are
extracted, so the frequency can be effectively selected to avoid the happening of the resonance phenomenon. Table 2 shows that results deviation between finite calculating and the modal experiment is within 10%. From figure 5 we get that the natural vibration pattern are basically the same which shows the finite modeling for the flexible skin of trailing edge is an effective way.

6. Conclusion
This paper introduces the way of design and manufacture of the flexible skin of the composite trailing edge, finite modeling and simulating and modal experiment. The conclusion are as follows:

① The main reason for the existence of the error in the two methods is that the additional mass of the acceleration sensor is not considered during the modeling process, as well as the error during data collection and data processing; ② The finite element modeling method is an effective way analyze the structure modes; ③ Through vibration experiment for the trailing edge of the morphing wing, the natural frequency of the structure is obtained as 13.08Hz, which lays effective data available for subsequent dynamic performance studies.

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