MULTIPLE FREQUENCIES OPTIMIZATION OF COMPOSITE WING FLUTTER MODEL

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Keywords: *dynamic similarity, composite materials, flutter, mode, frequency, genetic algorithm*

Abstract

The layer wise optimization of a composite wing flutter model is presented in this paper. The layer wise optimization provides a procedure for the application of fiber reinforce composite to meet the requirements of dynamic similarity between the wing and its flutter model. The layer wise optimization is in terms of stacking sequence and layer numbers of laminates. The design variables are taken for the numbers of symmetric layers of the wing flutter model structures and sets of fiber orientation angles in the layers, while multiple inherent vibration frequencies of the wing flutter model are considered to be objects in the optimization. Meanwhile, composites strength of the wing flutter model under specified air pressure is treated as the constraint condition. The vibration problem and composites strength are solved by finite element method separately and genetic algorithm is applied to the optimization problem. In numerical calculations, optimizations of the lowest frequencies of a composite wing flutter model are conducted, validating the efficiency of the procedure presented.

1 Introduction

Because of the advanced elastic properties and tailoring capability, also the potential for incorporating optimum techniques into the design of candidate structures, composite materials are mainly preferred in the structures of aerospace, marine and automobile engineering. Composites are especially useful in the design of structures' dynamic properties. Hence, among composites optimization problems, optimal designs of composites with frequency constraints or objects are extremely useful in dynamic problems of structures. For example, the fundamental vibration frequencies of structures should be restricted to avoid resonance[1]. Similarly, the minimum separation between the lowest bending and torsional frequencies of composite wings could be governed to improve the flutter characteristics of an aircraft[2].

Flutter, which has been one of the airplane's potential problems, is a phenomenon of dynamic instability of the airplane occurring at a critical velocity of the airflow passing over it. In order to avoid flutter inside the flight envelope curve of the airplane, flutter analysis and test have been significant proportions of the design of airplane. In fact, the dimension and material system of airplane flutter model are always transferred in order to meet the smaller size of the wind tunnel compared with the original airplane. Therefore, the basic principle of the design of airplane flutter model is the dynamic similarity between the model and the original airplane.

With the requirements of dynamic similarity, the airplane and its flutter model should be in good agreement in their inherent vibration frequencies. However, the traditional flutter model design method, which deduces the structures of the model, needs large quantities of manual and computational work. In recent years, composite materials are increasingly applied to the airplane flutter model, not only improving the structure characteristics, but also increasing working efficiency.

The purpose of the present work is to show an optimization of composite structures in a wing flutter model. The layer wise optimization approach is applied in this optimal study, with the objects of multiple frequencies and constraint of composites strength. More significantly, a highly-efficient optimization method combines finite element method and genetic algorithm is validated.

2 Dynamic Similarity of Flutter Model

2.1 Flutter Function of airplane

Because of the restriction of the wind velocity supported and the dimension of the wind tunnel, it has been always difficult to utilize the original airplane to conduct the flutter test. Hence, the dimension of the airplane should be reduced in terms of the dynamic similarity.

The dynamic equation of flutter analysis is as follows:

$$-[M]\{q\}+(1+ig)/\omega^2[K]\{q\}=-\rho[C]\{q\} \quad (1)$$

where [M] presents the mass matrix of the structure, while [K], [C], and {q} are the stiffness matrix, aerodynamic load matrix, and coordination vector, respectively. Then, ρ is the density of the air, g is the damping coefficient, and ω is the flutter frequency.

2.2 General Procedures for Submission

$$\det([K]-\omega^2[M])=0 \quad (2)$$

It can be concluded from the dynamic equation (2) that, in the dynamic similarity design, only three parameters should be used, including length, time and mass. Specifically, in the design of flutter model, L-the size of the model, V-maximal velocity provided by the wind tunnel, and ρ-the density of the airflow in the wind tunnel are considered as the variables. Hence, parameters of the model can be calculated through the similarity ratios k_L, k_V, k_ρ.

For example, the discount ratio of the inherent vibration frequency of the flutter model is given by

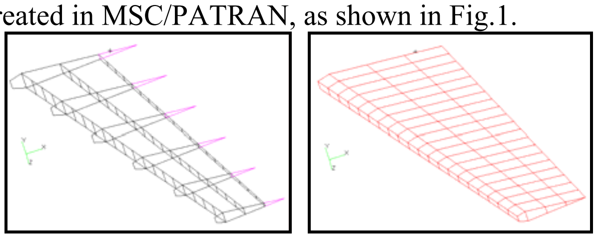
$$k_\omega = k_V k_L^{-1} \quad (3)$$

Since the frequencies of the wing are known already, those of the flutter model can be obtained from Eq.(3). Then the frequencies are used to optimize the composite structure of the model.

3 FE Model of Wing Flutter Model

3.1 Wing Flutter Model Considered

The structure studied is a composite airplane wing flutter model. To validate more accurate analysis a FE model of a wing flutter model is created in MSC/PATRAN, as shown in Fig.1.



a) Beams & ribs b) Envelope

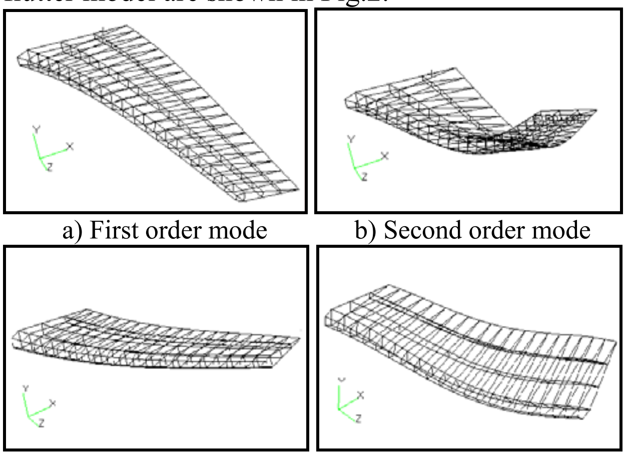
Fig. 1. FE model of the wing flutter model

The flutter model consists of 3 portions, beams, ribs and envelope, each of which are made of composite laminates. The root of the wing flutter model is fixed supported, with all of the 6 freedoms of each node are constrained. The total numbers of layers are defined as M for beams, N for ribs, respectively. Symmetrically laminated plates with even numbers of layers are considered for the envelope, the number is defined as 2K.

To simulate the air force loaded on the wing during flutter test in the wind tunnel, the air pressure is assumed to be distributed along transverse direction of the wing. Hence, in the optimization of the wing flutter model, the composites strength under the air pressure has to be considered as the constraint condition.

3.2 Inherent Vibration Mode of the Model

In the present optimization study, frequencies of the lowest inherent vibration modes of the wing flutter model are taken to be objects. In order to validate more accurate analysis, the inherent vibration modes of the model are analyzed using MSC/NASTRAN. The lowest four modes of the flutter model are shown in Fig.2.



a) First order mode b) Second order mode

c) Third order mode d) Forth order mode

Fig. 2. Inherent vibration modes of flutter model

In many cases of mode analysis, the specified modes of the structure should be tracked so that one can get the according frequencies, and that is called "Mode Tracking". However, in the present study, the differences among the frequencies of the model's lowest modes are large enough that the mode tracking is not necessary. Therefore, in NASTRAN, it is convenient to get the frequencies of the specified modes through the mode numbers.

Moreover, so as to meet the constraint condition under air pressure, the composites strength should be also verified in NASTRAN. The strength is evaluated through Tsai-Wu failure criterion, based on the first ply failure mode. It should be noticed that, as the mode analysis and strength evaluation are dealt in different solution modules in NASTRAN, the two analyses are treated separately.

4 Optimization and Genetic Algorithm

4.1 Optimization Problem

The layer wise optimization approach is applied in this optimal study. Frequencies of multiple lowest modes are used as the objects in the present optimization. The design variables are taken to be a set of fiber orientation angles in the 2K layers of the envelope.

$$\theta=[\theta^1/\theta^2/\ldots/\theta^k/\ldots/\theta^K]s \qquad (4)$$

where θ^k is the fiber orientation angle in the kth layer. Moreover, numbers of layers in the beams (M) and ribs (N) are also considered as the variables.

Therefore, the optimization problem can be described as follows:

$$\text{Min} \quad \Omega_i = |F_i-F^*_i|/ F^*_i \qquad i=1,2,\ldots,n \qquad (5)$$

$$\text{St.} \quad M^L \leqslant M \leqslant M^U$$

$$N^L \leqslant N \leqslant N^U$$

$$K^L \leqslant K \leqslant K^U$$

$$R < 1$$

$$\theta^k \in [0^{\circ},-45^{\circ},45^{\circ},90^{\circ}] \qquad k=1,2,\ldots,K$$

Ω_i is the error between the target frequency F^*_i and the optimal one F_i, in the total n modes required. The lowest and highest bounds are given for M, N, and K, respectively. R is the strength ratio of the structure under the given air force, which derives from Tsai-Wu failure criterion. Fiber orientation angle θ^k can only be chosen from 0°, -45°, 45°, and 90°, while those of the beams and ribs are considered to be constants.

4.2 Solution Flow

For many practical problems, the design of composite laminates are discrete optimization problems, as the ply orientation angles are limited to a small set of angles, such as 0°, -45°, 45° and 90°. In recent years, application of genetic algorithm has been increasingly popular in the composite optimization problem.

Genetic algorithm has been proved suitable for composite optimization problems, not only because its ability of treating discrete variables, but also because its little requirement of the information of object functions. Hence, it is convenient to utilize genetic algorithm to solve the optimization problems when it is hard to get the explicit object functions, for example, those complex structures as wings. There are several typical steps in a standard genetic algorithm. Firstly, an initial population with random genes is created. Then, the fitnesses of the population are evaluated and parents are chosen from the current population. Next, crossover and mutation operators are applied to create the new generation. All of the steps above are cycled until some convergence criterion is met.

In the present study, genetic algorithm is used to accounted for the optimization, where the genetic size is set to be 32, rates of crossover, mutation and migration are 1.0, 0.01 and 0.5, respectively. The solution flow is shown in Fig.3.

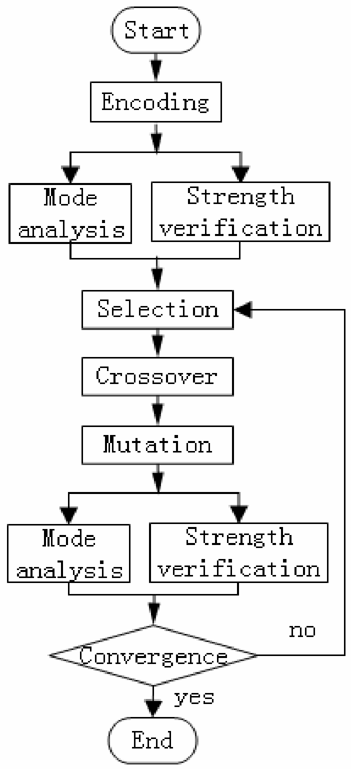


Fig. 3. Flow chart of the optimization problem

5 Numerical Calculations

Optimization is performed to the composite wing flutter model in 3.1. All of the laminates in the structures of the wing model are made of graphite-epoxy. The material constants are E_1=181GPa, E_2=10.3GPa, G_{12}=7.17GPa, and v_{12}=0.28.

Two cases of optimization are considered:

- The lowest 3 frequencies of the wing flutter model are taken to be objects, as shown in Table 1.
- The lowest 4 frequencies of the wing flutter model are taken to be objects, as shown in Table 2.

Table 1. Optimization of the lowest 3 frequencies of the wing flutter model

Variables				
M	10			
N	7			
K	4			
R	0.217			
θ	[90º/-45º/45º/0º]s			
Objects				Ω_i
F^*_1	70 Hz	F_1	70.49 Hz	0.69%
F^*_2	310 Hz	F_2	309.79 Hz	0.07%
F^*_3	388 Hz	F_3	388.21 Hz	0.05%

Table 1 presents the optimum solution obtained for the wing flutter model with frequencies of the lowest 3 modes as objects. The optimal stacking sequence of the envelope of the wing is [90^o/-45^o/45^o/0^o]s, while there are 10 and 7 layers in beams and ribs separately, with constant fiber orientation angle. According to the figures, the optimal frequencies fit the target ones well. The largest error between the optimal frequency and the specified one occurred in the first frequency, only 0.69%. Meanwhile, the composites strength ratio is far less than 1, which indicates the safety of the structure under the given air pressure.

Table 2. Optimization of the lowest 4 frequencies of the wing flutter model

Variables				
M	17			
N	5			
K	5			
R	0.21			
θ	[45º/-45 º /0 º /90 º /0 º]s			
Objects				Ω_i
F^*_1	68Hz	F_1	68.53Hz	0.77%
F^*_2	306 Hz	F_2	307.99 Hz	0.65%
F^*_3	376 Hz	F_3	382.09 Hz	1.62%
F^*_4	441 Hz	F_4	445.88 Hz	1.11%

Table 1 presents the optimum solution obtained for the wing flutter model with frequencies of the lowest 4 modes as objects. The optimal stacking sequence of the envelope of the wing is [45^o/-45^o/0^o/90^o/0^o]s, while there are 17 and 5 layers in beams and ribs separately, with constant fiber orientation angle. As can be seen from the figures, since more objects are required, the errors between optimal frequencies and target ones increase, with the largest one 1.11% in the fourth frequency. However, the optimal frequencies fit the target ones well, when the composites strength ratio is far less than 1, indicating the safety of the structure under the given air pressure.

6 Conclusions

A layer wise optimization approach is applied in a composite wing flutter model to achieve multiple frequencies of the lowest inherent vibration modes. Meanwhile, the composite strength under given air pressure is taken to be the constraint condition. The layer wise optimization provides a procedure for the application of fiber reinforce composite to meet the requirements of dynamic similarity between the wing and its flutter model. The layer wise optimization is in terms of stacking sequence and layer numbers of laminates in the wing flutter model structures.

With the idea of this approach, finite element method is used to analysis the modes and strength of the wing model. Also, the genetic algorithm is proposed to solve the optimization problem. Numerical calculations are conducted for the wing flutter model. It has been shown that the errors between optimal frequencies and the target ones increase when more frequencies are required. However, the approach presented has been proved efficient for the multiple frequencies optimization of composite structure. It could be anticipated that the multiple frequencies optimization which combines finite element method and genetic algorithm will be extended as a practical method in airplane design and other important industrial fields.

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