Research on flutter method for three dimensional wing rudder

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Abstract. Aiming at providing high efficiency and accurate flutter analysis for high speed aircraft in transonic flow, flutter analysis in frequency domain based on three-dimensional wing rudder is employed for AGARD 445.6 wing. The simulation results are consistent with both experiment and reference, which validates the flutter mechanism in the subsonic and transonic regions. This simulation not only improves the accuracy of flutter analysis, but also saves calculation time and improves efficiency. Thus, it lays a foundation for high speed aircraft in transonic flow flutter prediction.

1. Introduction

Aerodynamic performance prediction is the primary consideration in many structure design [1-3]. Flutter is a large-scale vibration caused by the coupling of unsteady aerodynamic, elastic and inertial forces of elastic structures subjected to uniform air flow. When the flutter occurs, if the structure's speed exceeds the critical flutter speed, a small disturbance will cause divergent vibrating, leading to catastrophic structural damage within a few seconds or even tens of milliseconds [4-5]. Therefore, accurate prediction of structure flutter analysis plays an important role in aircraft dynamic analysis and structural optimization design. Recently, using the fluid-structure interaction simulation to analyze the mechanism of structural flutter and obtain its results has received growing attention in the aeroelasticity area [6-7].

The traditional aircraft-oriented flutter simulation is the frequency-domain flutter analysis method. This method derives the aerodynamic force on the surface assuming that the structure is in the critical state of flutter, and finally obtains the flutter speed and frequency [8]. However, this method is based on a planar model without taking into account detailed information of the structure such as thickness and angle of attack, which affects the accuracy of the flutter analysis results. Thus, researchers proposed a time-domain flutter analysis method for three-dimensional structural models, which precisely simulates the motion of the structure in the flow field. Nevertheless, it requires plenty of time for flutter boundary calculation [9]. Therefore, the research on simulation method which provides efficient and accurate flutter analysis for aircraft structure is of great significance in aircraft structure design and engineering practice.

Based on Nastran, this paper extends a flutter method to three dimensional wing rudder. Test case of AGARD WING 445.6 is investigated to confirm the validity of the method. Through comparing results in the experiment and reference, it proves that this method can improve the accuracy of the flutter analysis while significantly save computing cost. In addition, this method can be expanded to transonic unsteady flutter of different airfoils, laying a foundation for a deep understanding of the flutter mechanism and the efficient and accurate flutter prediction.
2. AGARD WING 445.6 Standard Model

The AGARD WING 445.6 wing was first used in the 1961 NASA Langley Center TDT wind tunnel test. This benchmark model is made by mahogany and is covered with small holes. Its airfoil is NACA65A004 along the flow direction. Plane characteristic parameters are as follow: the aspect ratio is 1.644, tip root ratio is 0.6529 and quarter chord wing sweep angle is 45°. In the wind tunnel test, the No. 3 wing model with weak stiffness occurred flutter, which has become the internationally accepted assessment standard for the simulation method of transonic wings flutter characteristics [10-11].

The plane shape and geometric parameters of the model are shown in Figure 1. The material density is 351.98kg/m³. The elastic modulus of x, y, and z directions of the wing are: 1GPa, 1.54GPa, 1Gpa. The shear moduli of the three directions of the wing are 2.6GPa. The Poisson's ratio is 0.31.

![Figure 1. AGARD WING 445.6 geometric model](image1)

3. Three dimensional wing rudder flutter method

3.1. Modeling Method

According to the reference [11], a three-dimensional model of the wing is obtained using Pro/E Creo. The main steps are as follow:

a) Generate a two-dimensional airfoil section model based on NACA 65A004 airfoil profile data provided in the literature.

b) Around the main axis of the wing, superimpose the two-dimensional airfoil at a quarter-chord length along the 45-degree direction to generate a three-dimensional surface model.

c) Use the surface model to generate a three-dimensional rudder model first. Then smooth transition trimming is performed on the wing tip and wing root. Finally, the three-dimensional rudder model is smoothed.

Based on the geometric parameters of the wing standard model AGARD WING 445.6, the final 3D solid model is derived as shown in Figure 2.

![Figure 2. AGARD WING 445.6 simulation geometry model](image2)

3.2. Frequency domain flutter analysis method

The establishment of aeroelastic model directly determines whether the results of flutter analysis are correct. It includes the setting of aerodynamic parameters, the selection of reduced frequency, and the method of spline interpolation. There are two common methods for calculating flutter: KE method and PK method. The PK method derives the flutter results through obtaining eigenvalues of a real number matrix. This method also shows certain subcritical characteristics. Even the calculation is more complicated, PK method is more applicable than KE method [12].
According to the reference [13-14], considering characteristics of the three-dimensional rudder structure model of the wing, the PK method is selected as the flutter calculation method as the flutter calculation method and the flutter equation is:

$$\left[\begin{array}{c}
M_{k_{\text{th}}} p' + \left(\frac{1}{2} \rho V^2 Q_{\text{th}} k_p + \frac{1}{2} \rho V^2 Q_{\text{th}}^b p\right) \end{array}\right] = 0$$

(1)

Where $Q_{\text{th}}^b$ is modal aerodynamic damping matrix, $Q_{\text{th}}^b$ is modal aerodynamic stiffness matrix, $p$ is characteristic value.

As shown in Equation (2), the range of reduced frequency $k$ can be calculated according to the speed $V$ and range of natural frequency $\omega$, and the relevant values can be automatically derived using Nastran.

$$k = \frac{\omega c_{\text{ref}}}{2V}$$

(2)

Where $c_{\text{ref}}$ is the reference chord length.

The main technical route is as follows:

a) Set the atmospheric density and Mach number; b) Assume the flight speed; c) For each structural mode $\omega_i$, assuming the initial reduced frequency $k_i^{(0)}$ equals to $\frac{\omega_i c_{\text{ref}}}{2V}$, then obtaining the aerodynamic coefficient; d) Obtain two characteristic value $p$ of the flutter equation (1), where $p_1 = \gamma k_{i1} + ik_{i1}$, $p_2 = \gamma k_{i2} + ik_{i2}$; e) Select the imaginary part of characteristic value which is close to the structural mode $\omega_i$ and used as the initial reduced frequency of the next iteration $k_i^{(1)}$; f) During the iteration process, when the difference between $k_i^{(j)}$ and $k_i^{(j-1)}$ is less than the preset index, stop the iteration and the reduced frequency value obtained at this time is the final solution.

MSC.Nastran is used to calculate AGARD WING 445.6 flutter results using PK method. Firstly, establish the aerodynamic grid of the wing, load various conditions, and modify the generated bdf file.

Secondly, select the spline interpolation method. Different from the traditional method, which uses the shell element to generate a two-dimensional model, this article uses a three-dimensional rudder model for flutter analysis. And hence the aerodynamic interpolation method is set to the TPS interpolation method (a spline method for high-level aerodynamic model interpolation in three-dimensional space).

Finally, different aerodynamic density and speed range under $Ma = 0.499, 0.678, 0.901, 0.96, 1.072, 1.141$ are obtained. Corresponding to different Mach number, the aerodynamic density and speed range are shown in Table 1.

| Mach number | Aerodynamic density($kg/m^3$) | Speed range (m/s) |
|-------------|-------------------------------|------------------|
| 0.499       | 0.4277                        | 100–200          |
| 0.678       | 0.2082                        | 100–300          |
| 0.901       | 0.0995                        | 150–350          |
| 0.960       | 0.0634                        | 200–400          |
| 1.070       | 0.0551                        | 250–450          |

Using Equation (2), the Mach number-reduced frequency pair could be set for flutter analysis.

4. Agard wing 445.6 results and analysis

4.1. Agard wing 445.6 modal results and analysis
Use Nastran to obtain modal results. Based on the three-dimensional rudder model, select the Tetmesher mesh generator and the topology type, set the element size, the material properties, element properties and impose constraints. The natural modal distribution range of the AGARD wing 445.6 is relatively wide, and thus the results of the first four orders can be analyzed.

Table 2 shows the first four modal frequencies from simulation values, experiment and reference [11, 15]. The vibration mode comparison of Nastran simulation and NASA experiment is shown in Figure 3.

| Natural frequency | Experiment | Reference | Simulation |
|------------------|------------|-----------|------------|
| First order      | 9.5992     | 9.74      | 9.2205     |
| Second order     | 38.165     | 38.4      | 37.905     |
| Third order      | 48.3482    | 50.3      | 54.737     |
| Fourth order     | 91.5448    | 91.8      | 94.713     |

**Figure 3.** AGARD WING 445.6 vibration mode of simulation and experiment

It should be pointed out that the first mode of simulation shown in Figure 3 a) is downward, while the mode given in Figure 3 b) of the experiment is upward. This results is only caused by a phase difference of 180°, the first modes of simulation and experiment are still consistent. There are no phase differences between the other analytical and experimental modes. Thus it concludes that simulation vibration modes are in good agreement with NASA experimental modes.

According to the natural frequency values in Table 3 and the vibration mode in Figure 3, the simulation results are basically consistent with the experimental and reference results and the error range is relatively small. The mode shape and frequency are in reasonable agreement with the experimental results. It indicates that the three-dimensional rudder modeling method is correct and feasible, and can accurately obtain the modal analysis results.
4.2. Agard wing 445.6 flutter results and analysis

The first four velocities and damping at different Mach numbers are showing in v-g diagrams, and the first four velocities and frequencies at different Mach numbers are depicted in v-f diagrams.

Taking the flutter results of Ma = 0.499 as an example, as shown in Figure 4a), Figure 4b) gives the relevant results in Reference [10].

Figure 4 proves that the flutter analysis results at Ma = 0.499 are basically consistent with the v-g and v-f curve trends obtained by the reference [10], and the critical flutter velocity and flutter frequency gives satisfactory accuracy comparing with the reference results, which proves that the correctness of the flutter analysis method.

Similarly, flutter results at Ma = 0.678, 0.901, 0.96, 1.072, 1.141 can also be obtained.

Introducing flutter speed coefficient $V_F$:

$$ V_F = \frac{V}{b\omega_a \sqrt{\mu}} $$

Where $V$ is the inflow velocity, $b$ is the reference length (generally defined as half of the root chord of the wing), $\omega_a$ is the reference frequency (generally defined as the first order torsion frequency of the wing), $\mu$ is the mass ratio.

The flutter characteristics of wings in transonic region can be analyzed by using the flutter velocity coefficient. Depict the curve of flutter speed coefficient with Mach number, i.e. flutter speed characteristic curve, as shown in Figure 5:
Figure 5. Flutter speed characteristic curve of transonic wing

According to Figure 5, the calculated and experimental values of transonic flutter speed characteristics are generally consistent and slightly deviated. Compared with the data in reference [10], the simulation results are closer to the experimental results. Thus the accuracy and correctness of the flutter analysis method used in this article are validated again. In addition, flutter results clearly reflect the physical characteristics of "pits" in the transonic region when the critical flutter speed of transonic wings changes with the Mach number [16-18]. It shows that this kind of wing is rather dangerous when flying in the transonic region.

Similarly, the curve of flutter frequency coefficient (\( \omega \)) changing with Mach number can be depicted, i.e. flutter frequency characteristic curve, as shown in Figure 6:

Figure 6. Flutter frequency characteristic curve of transonic wing

Figure 6 shows that the flutter frequency characteristic curve obtained in this article is consistent with the experimental results and reference data trends. However compared with the literature data, the error between the simulation and experiment is larger, which may be caused by the geometric model accuracy and modal parameters. In addition, the aerodynamic calculation in flutter analysis uses the panel method for a three-dimensional rudder model, which may also cause errors. It can be subsequently compared and analyzed through the ZAERO software aerodynamic calculation results for the further research. In addition, similar to the flutter velocity characteristic curve, the relationship between the flutter frequency and the Mach number also indicates the physical characteristics of the appearance of "pits" in the transonic flutter critical velocity as the Mach number changes.

5. Conclusion

Based on the three-dimensional wing rudder, this article uses the frequency domain flutter simulation method to provide a flutter analysis and simulation process. Taking the NASA wing standard model AGARD WING 445.6 as an example, it is obtained the following conclusions:

1) According to the characteristics of high speed aircraft in transonic flow, an extended method for flutter analysis of wing rudder based on three-dimensional prototype model is explored.

2) This extended method is different from the traditional method, which analyzes flutter after model simplification. It uses a three-dimensional prototype structure for analysis, taking into account the influence of the thickness and angle of attack of the structure on the flutter. Therefore, it simulates the wing in the flow field accurately. The flutter simulation is basically consistent with the reference
and experiment, and the error is relatively small, which proves the correctness of the flutter analysis method used in this paper. This method can be further generalized and applied to solve the nonlinear fluid-structure coupling problem of the aircraft structure.

(2) Using this extended method, the transonic flutter mechanism has been analyzed and studied, which are consistent with other theoretical analysis.

(3) Compared with the traditional time-domain and frequency-domain analysis methods, the extended method greatly improves the accuracy of flutter analysis results while greatly saving computation time and improving efficiency.

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