Numerical study on influence of single control surface on aero elastic behavior of forward-swept wing

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Abstract. In order to study the influence of elastic forward-swept wing (FSW) with single control surface, the computational fluid dynamics/ computational structural dynamics (CFD/CSD) loose coupling static aero elastic numerical calculation method was adopted for numerical simulation. The effects of the elastic FSW with leading- or trailing-edge control surface on aero elastic characteristics were calculated and analysed under the condition of high subsonic speed. The result shows that, the deflection of every single control surface could change the aero elastic characteristics of elastic FSW greatly. Compared with the baseline model, when leading-edge control surface deflected up, under the condition of small angles of attack, the aerodynamic characteristics was poor, but the bending and torsional deformation decreased. Under the condition of moderate angles of attack, the aerodynamic characteristics was improved, but bending and torsional deformation increased; When leading-edge control surface deflected down, the aerodynamic characteristics was improved, the bending and torsional deformation decreased/increased under the condition of small/moderate angles of attack. Compared with the baseline model, when trailing-edge control surface deflected down, the aerodynamic characteristics was improved. The bending deformation increased under the condition of small angles of attack, but torsional deformation decreases under the condition of moderate angles of attack. So, for the elastic FSW, the deflection of trailing-edge control surface play a more important role on the improvement of aerodynamic and elastic deformation characteristics.

1. Introduction

Compared with the traditional aircraft aerodynamic layout, Forward-Swept Wing (FSW) has significant advantages in the configuration of the aircraft aerodynamic performance and operating performance [1, 2], but the aircraft static aero elastic divergence problem of FSW seriously limits its practical application and development. The flexibility of structure in nowadays aircrafts increases
gradually, which also exacerbates the aircraft static aero elastic divergence problem, so it is of great significance to study on static aero elastic divergence problem of FSW.

Before the advent of numerical calculation method, the aero elastic simulation is mainly through experiments. This method is of high cost, high risk and difficult to operate. With the computational fluid dynamics (CFD) and computational structural dynamics (CSD) development and the rapid improvement of computer hardware, the CFD/CSD coupling method for aircraft static aero elasticity has developed rapidly[3]. On this basis, the scholars at home and abroad have done a lot of researches for the static aero elasticity of forward-swept wing aircraft. Polli [4] has analyzed aerodynamic thermal elastic response and stability of the composite wing with coupling numerical method, Zhang [5] with his partners has analyzed the aerodynamic characteristics of the flexible wing with elastic deformation.

Active Aero elastic Wing (AAW) technology is a new generation of technology for aircraft design in the United States raised since 1980s[6]. A large number of AAW technology studies have been carried out in recent years at home and abroad [7-9], the results show that the vehicle performance is greatly improved with multi-control surfaces, and it also takes the design of aerodynamic aspects, active control and structure design into consideration. As a result, the unfavorable factors of the flexible structure are transformed into favorable factors. In this paper, the calculation and analysis of static aero elastic characteristics of forward-swept wing with leading- and trailing-edge control surfaces are performed based on the CFD / CSD loosely coupled numerical method. Due to the application of AAW technology, the deflection of multi-control surfaces will become the main future advanced fighter control. As a result, the study of multi-control surface deflection is also important for aircraft static aero elastic response effect.

2. The calculation method and verification

The three-dimensional Reynolds-averaged Navier-Stokes (RANS) equation was used to calculate aerodynamics. In this paper, the integral form of the conservative three-dimensional N-S equations could be written as follows:

$$\frac{\partial}{\partial t} \int_{V} Q dV + \int_{S} \left( F^{I} - F^{V} \right) \cdot n dS = 0$$

(1)

Where: Q, FI, FV, Ω and S were the solution vector, in viscous flux vectors, viscous flux vectors, control volume and surface of control volume, respectively; and n respected the surface normal.

Shear stress transport (SST) K-Omega model was used as turbulence model. Flow control equations was presented by nonlinear partial differential equations. The exact analytical solution generally could not be given except doing discretization. Therefore, the finite volume method and finite element method were used to disperse the flow field and the structures into finite small units, respectively. The polyhedral mesh was more efficient for calculation and had high convergence precision[10], so it was chosen for mesh generation of the flow field.

The transmission of aerodynamic force and displacement data between CFD mesh and CSD mesh node was carried out by constant volume transformation (CVT) method. Besides the radial basis function interpolation method was used to deform and update the CFD mesh to improve the efficiency of calculation[11].

The coupling methods were used to resolve the coupling problem between CFD and CSD calculation in time domain. At present, the coupling methods mainly included tight coupling and loose coupling methods. In order to improve the computational efficiency and reduce the computational complexity, CFD/CSD loose coupling static aero elastic calculation method was adopted for numerical simulation. The calculation process was shown in Figure1.
In order to verify the accuracy of the calculation method, HIRNASD aero elastic example was used to verify the method[12]. Firstly, the flow field and the model aircraft HIRENASD wing structure were generated by polyhedral mesh and tetrahedron mesh, respectively. The initial conditions for calculation were $\alpha = 2^{\circ}$, $Ma=0.8$, $Re=2.35\times10^7$ and $q/E=4.8\times10^{-7}$. Where $q$ was the dynamic pressure in the calculation and $E$ was Young's elastic modulus of structure model.
Figure 3. Pressure coefficient of different positions

As shown from Figure 3, the numerical method could fit the experimental value better and meet the calculation requirements of this paper.

3. Calculation model

The model of FSW layout for computation was close to reference [13]. In order to study the influence of static elastic response of the control surfaces, the aircraft wing tip was additionally provided with a leading-edge control surface (LC) and trailing-edge control surface (TC). The geometric outline was shown in Figure 2.

The specific control surface model size was shown in Table 1. Where \( c_{TW} \) and \( S \) were span wise length of wingtip chord length and semi-span. \( \delta_L \) and \( \delta_T \) were the definitions of the leading- and the trailing-edge control surface skewness, and \( \delta_L \) and \( \delta_T \) were positive when the LC deflected up and TC down.

| Item     | Chord length | Span wise length | Span wise position |
|----------|--------------|------------------|-------------------|
| LC       | 0.1\( c_{TW} \) | 0.2\( s \)      | 0.97\( s \)       |
| TC       | 0.2\( c_{TW} \) | 0.2\( s \)      | 0.97\( s \)       |

The AAW technology was usually used in two ways[8]: the same deflection (LC deflected up and TC down) and different deflection (LC and TC deflected down). Therefore, it was studied the effects of the deflection of single control surface as the basis of the study of FSW static elastic response. The Brief introduction of computational models used in this paper were shown in Table 2.

| Abbreviation                  | \( \delta_L \)     | \( \delta_T \)     |
|-------------------------------|---------------------|---------------------|
| Baseline                      | 0°                  | 0°                  |
| LC deflecting alone           | -30°~30°            | 0°                  |
| TC deflecting alone           | 0°                  | 10°~30°             |

The computation conditions of flow field boundary were \( \text{Ma}=0.6, \text{Re}=2.32\times10^6, \rho=1.23 \text{ kg/m}^3, \text{T}_\infty=288.15 \text{ K and P}_\infty=1.01\times10^5 \text{ Pa} \). The wing was fixedly connected in the body. Different materials
were used for the main body[14], wing and control surfaces. The structural material properties for the wing and main body were E1=0.89 GPa, E2=1.54 GPa, \(\nu=0.31\), G=2.6 GPa, \(\rho_1=381.98\) kg/m\(^3\); and the structural material properties for control surfaces were E=72 GPa, \(\nu=0.34\), \(\rho_2=2700\) kg/m\(^3\). Where E1 and E2 were elastic modulus of the wing along the chord and stretch. G, \(\nu\) and \(\rho\) were the shear modulus, Poisson's ratio and density, respectively.

The control with the longitudinal aerodynamic characteristics of forward swept wing and elastic deformation characteristics were only studied, so half model was used to simplify the following analysis. The number of polyhedral mesh of the half model in fluid domain was 4 million, and the number of tetrahedral mesh in structural domain was 100,000.

4. Aerodynamic characteristic

The elastic FSW model was only studied. Therefore, elastic and rigid aerodynamic characteristics of FSW models must be compared. Taking the baseline model, which the control surfaces didn’t deflect, as an example, when Ma=0.6, Re=2.32×10\(^6\), the calculated elastic and rigid aerodynamic characteristics of forward swept wing model were shown in Figure 4.

![Figure 4. Aerodynamic characteristics of elastic and rigid Baseline models](image)

As shown in Figure 4 (a), when \(\alpha<14^\circ\), the lift coefficients of elastic wings were greater than those of rigid wings, but the result was opposite when \(\alpha>14^\circ\); When \(\alpha<8^\circ\), the \(C_L^\alpha\) of elastic wings were greater than those of rigid wings, which was smaller when \(\alpha>8^\circ\); In addition, the rigid wing and elastic wings had little difference in the stall angle of attack, both at about 40\(^\circ\); Compared with the rigid wing, the maximum lift coefficient elastic wing decreased about 10.78%. Therefore, the bending
and torsional deformation of the elastic wing led to the increase of the effective angle of attack, the lift characteristics at the smaller angle of attack were better than those of the rigid wing; But at higher angle of attack, the separation of air flow on the wing surface was more serious, and the lift characteristics became worse; In addition, as the elastic wing produced a forward torsion, the frontal area increased, which caused that drag characteristic was worse than that of the rigid wing; As shown in Figure 4 (b), the drag coefficients of the elastic wing were always greater than that of the rigid wing at the same angle of attack.

According to figure 4 (c), the aerodynamic efficiency of elastic forward-swept wing was slightly higher than that of the rigid wing at small angle of attack, but it was far lower than that of the rigid wing at high angle of attack. The maximum lift-drag ratio of the elastic wing was about 7% lower than that of the rigid wing, and the angle of attack at the maximum lift-drag ratio Kmax was achieved about 2° ahead of that of the rigid wing. From Figure 4 (d), when \( \alpha < 4° \), the pitching moments of elastic wing were greater than rigid wing, which were opposite when \( 4° < \alpha < 24° \), the pitching moments of elastic wing and rigid wing were almost equal when \( \alpha > 24° \).

From the analysis above, the aerodynamic characteristics of elastic and rigid forward-swept wing models were obviously different.

When LC deflected alone, the aerodynamic characteristics of the elastic LC model were shown in Figure 5 under the conditions of \( Ma=0.6 \) and \( Re=2.32\times10^6 \).

According to figure 5 (a), when LC deflected up, compared with the baseline model, it caused the lift coefficient decrease under the condition of \( \alpha < 12° \), and the greater the skewness was, the greater the magnitude of lift coefficient decreased; It caused the lift coefficient increase when \( \alpha > 12° \), and the increasing magnitude decreased with the increase of the skewness. The increase of effective angles of attack at outside partial wing was caused by the upward deflection of LC, the stall angle of attack of wing outer segment was ahead at a low angle of attack, so the lift decreased. The stronger leading edge vortex formed under the condition of high angles of attack, which caused the increase of lift.

Compared with the baseline model, the upward deflection of LC led to the increase of lift coefficient. As the skewness increased, the increasing magnitude of lift coefficient would increase first and then decrease. The downward deflection of LC made the suction peak of the wing leading edge decrease, adverse pressure gradient decrease and the flow separation delay. As a result, the lift increased [15].
According to figure 5 (b), compared with the baseline model, the frontal area increased when LC deflected up. As a result, drag coefficient increased slightly. The magnitude increased slightly with the increase of skewness; On the contrary, the downward deflection of LC had little impact on drag coefficient.

According to Figure 5 (c), compared with the baseline model, the upward deflection of LC made the lift-drag ratio decrease, and the greater the skewness was, the higher decrease magnitude of lift-drag ratio would be. The situation would be opposite when LC deflected down.

According to figure 5 (d), compared with the baseline model, when LC deflected up/down, the pitching moments would decrease/increase under the condition of $\alpha < 12^\circ$. The result would be opposite when $\alpha > 12^\circ$. 
When the TC deflected alone, the aerodynamic characteristics of the elastic TC model were calculated under the conditions of $Ma=0.6$ and $Re=22.32\times10^6$, which is shown in Figure 6.

According to Figure 6 (a), compared with the baseline model, the downward deflection of TC led to the increase of lift coefficient, and the magnitude would increase with the increase of skewness, so did the camber of wing’s outer section and the lift.

According to Figure 6 (b), the downward deflection of TC made the frontal area of the wing’s outer section increase. As a result, the drag coefficient increased. The magnitude increase with the increase of skewness.

According to Figure 6 (c), compared with the baseline model, when TC deflected down, the maximum lift-drag ratio decreased, the aerodynamic efficiency was reduced, and the decreasing magnitude of $K_{max}$ increased with the increase of skewness. According to Figure 6 (d), compared with the baseline model, when TC deflected down, the pitching moment increased, and the increasing magnitude of $C_m$ increased with the increase of skewness.

5. Elastic deformation characteristics
When $\alpha=4^\circ$, the deflections of the wing in Z direction caused by the deflections of control surfaces were shown in Figure 7.
When the control surface deflected alone, the calculated leading wing tip deflection $w_T$ changed with the increase of the angle of attack and the result was shown in Figure 8. When $\alpha < 8^\circ$, the leading wing tip deflections of LC and TC models increased linearly with the increase of the angle of attack sharply; when $\alpha > 8^\circ$, the change of $w_T$ with the increase of angle of attack was very small.

According to Figure 8 (a), when LC deflected up or down, compared with the baseline model, $w_T$ decreased under the condition of $12^\circ < \alpha < 18^\circ$, and the decreasing magnitude increased with the increase of the skewness; $w_T$ increased slightly when $18^\circ < \alpha < 24^\circ$. According to Figure 8 (b), compared with the baseline model, with the downward deflection of TC, $w_T$ would increase. In addition, the increasing magnitude of $w_T$ increased with the increase of skewness.

When the control surface deflected alone, the wing tip torsional angle $\theta_T$ changed with the angle of attack. The result was shown in Figure 9. When the control surface deflected alone, under the condition of $\alpha < 8^\circ$, $\theta_T$ increased linearly with the angle of attack sharply, which was similar to the changing rule of $w_T$. Besides, $\theta_T$ was basically unchanged when $\alpha > 8^\circ$.

According to figure 9 (a), compared with the baseline model, when $\alpha < 12^\circ$, the deflection of LC caused the decrease of wing tip torsional angle. While, the magnitude increased with the increase of skewness; the situation was opposite when $\alpha > 12^\circ$. According to Figure 9 (b), compared with the baseline model, under the condition of $\alpha < 12^\circ$, when TC deflected down, $w_T$ increased. The magnitude increased with the increase of the skewness. When TC deflected down, under the condition of $\alpha < 12^\circ$, $\theta_T$ decreased and the magnitude increased slightly with the increase of skewness.
Figure 9. Variations of torsional angle of wingtip leading-edge of LC and TC models with angle of attack

Therefore, compared with the baseline model, when $\alpha < 12^\circ$, the deflection of control surface slowed down the bending and torsional deformation, but it would exacerbated that when $\alpha > 12^\circ$; The downward deflection of TC exacerbated the bending and torsional deformation when $\alpha < 8^\circ$, and it exacerbated the bending deformation, but slowed down the torsional deformation when $\alpha > 8^\circ$.

6. Conclusion

1) The aerodynamic characteristics of elastic and rigid forward-swept wing had obvious difference, the influence of structural flexibility on the aerodynamic performance must be fully considered of in design of forward-swept wings.

2) Compared with the baseline model, when LC deflected up, under the condition of small angles of attack, the aerodynamic characteristics was poor, but the bending and torsional deformation decreased. Under the condition of moderate angles of attack, the aerodynamic characteristics was improved, but bending and torsional deformation increased; When LC deflects down, the aerodynamic characteristics was improved, the bending and torsional deformation decreased/increased under the condition of small/moderate angles of attack.

3) Compared with the baseline model, when TC deflected down, the aerodynamic characteristics was improved. The bending and torsional deformation increased under the condition of small angles of attack. The bending deformation increased under the condition of small angles of attack, but torsional deformation decreased under the condition of moderate angles of attack.

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