Numerical Study on Influence of Canard Height on Aeroelastic Behavior of Forward-Swept Wing

Ning Wang*, Xinbing Su*, Binlin Ma#, and Xiaofei Zhangc

Air Force Engineering University, Xi'an, China

*Corresponding author e-mail: 1289603317@qq.com, #xinbing@sohu.com,
#mbinlin001@163.com, c343305484@qq.com

Abstract. Based on CFD/CSD loosely coupled numerical simulation method, the influence of canard height on the longitudinal aerodynamic characteristics and elastic deformation characteristics of forward-swept wing configuration model was calculated and analyzed. The results showed that the canard could effectively improve the aerodynamic characteristics of the forward-swept wing and delayed the stall angle of the main wing; the high-position canard wing can improve the aerodynamic characteristics and elastic deformation characteristics of the forward-swept wing better than the low-position canard wing; the detached vortex generated by the high-position canard wing can effectively improve the strength of the main wing vortex and improved wing root stall of forward swept wing. The results can provide some references for the design of forward-swept wing aircraft.

1. Introduction

Forward-Swept Wing (FSW) had good aerodynamic performance and maneuverability [1, 2]. The downwash of canard was more effective in delaying the separation of forward-swept wing roots. Canard vortex and FSW vortex were interfered with each other [3]. Different canard height position had different effects on the coupling of the two vortices. Suitable position would produce more favorable interference to the air flow of forward-swept wing, which could further improve the aerodynamic characteristics of FSW aircraft layout [4].

At present, more attention had been paid to the aerodynamic characteristics of the canard-FSW aircraft [5]. It showed that the FSW had obvious aerodynamic advantages, and the canard had an important influence on the aerodynamic characteristics of the forward-swept wing [6].

The FSW layout aircraft itself had a static aeroelastic divergence problem [7]. However, the aeroelastic divergence of FSW aircraft was more serious because of the increasing structural flexibility of wing in order to achieve high aerodynamic performance [8]. Therefore, it was important to study the influence of canard height on the aerostatic problem of FSW aircrafts.

2. The calculation method and verification

In this paper, the CFD/CSD loosely coupled static aeroelastic method was used to calculate the calculation model. CFD aerodynamic solution was the key of CFD/CSD coupling calculation. Reynolds average (RANS) three-dimensional Navier-Stokes (N-S) equation was used in the numerical calculation of flowfield. In the rectangular coordinate system, the velocity component of flow was
defined. The conservative three-dimensional Navier-Stokes equations in integral form can be expressed as follows:

$$\frac{\partial}{\partial t} \int_{\Omega} Q dV + \int_{S} (F^V - F^V_0) \cdot n dS = 0$$

(1)

Where: \( Q \) for the solution vector, \( G \) for the inviscid vector flux term, \( F^V \) for the viscous vector flux term, \( \Omega \) for the control volume, \( S \) for the control surface, \( n \) for the boundary normal vector. The Spalart-Allmaras (S-A) model was used for turbulence models. CFD was calculated using the finite volume method, and the flow field mesh was generated by polyhedral mesh [7]. The finite element method was used in the CSD calculation, and the flow structure mesh was generated by tetrahedral mesh. The constant volume transformation (CVT) method was used in the aerodynamic and displacement data transfer between CFD mesh and CSD mesh nodes [9]. The radial basis function (RBF) method was used in the river basin dynamic grid technology.

In order to reflect the authenticity of the results, the above method was verified by using HIRNASD aeroelastic example [10]. The flow field was generated by polyhedral mesh, and the structure of HIRENASD wing was generated by tetrahedral mesh. The number of flow field mesh and structure mesh was 3972383 and 186894, respectively. The flow field calculation conditions were \( M_a = 0.8 \), \( Re = 2.35 \times 10^7 \), \( q / E = 4.8 \times 10^{-7} \).

Where: \( q \) for the dynamic pressure and \( E \) or Young's modulus of elasticity.

The pressure coefficient curves of the cross-section near the wing with \( y/b = 0.95 \) were shown in the Figure 1. The calculated results were in good agreement with the experimental data in the elastic state. It showed that the wing deforms slightly in the elastic state, and the result page was closer to the actual situation. It can be seen from the figures that the calculation method used in this paper met the requirements of static aeroelastic analysis for forward-swept wings with different canard heights.

![Figure 1. The pressure coefficient when y/b=0.9](image1)

![Figure 2. Sketch of canard-FSW model](image2)

3. Calculation model

The model of canard-FSW layout for computation was close to reference [1]. The schematic diagram was shown in the Figure 2.

Among them, the fuselage length was 918 mm, the fuselage height was 94.8 mm, the main wing and the canard wing were all NACA 64A010 airfoil, wing and canard wing parameters as follows: the fuselage was an elliptical cylinder with a cabin, the nose part inclined downward 5 degrees.
Table 1. Brief introduction of computational models

| Model   | Swept angel of FSW | Swept angle of canard | Position of FSW | Position of canard |
|---------|--------------------|-----------------------|-----------------|-------------------|
| F01     | (−40°, −52.2°)     | −         | (74%L−32%H)     | —                 |
| C-F11   | (−40°, −52.2°)     | 49°, 25.5°           | (74%L−32%H)     | (32%L, 21%H)      |
| C-F12   | (−40°, −52.2°)     | 49°, 25.5°           | (74%L−32%H)     | (32%L, 21%H)      |
| C-F13   | (−40°, −52.2°)     | 49°, 25.5°           | (74%L−32%H)     | (32%L, 21%H)      |

The computation conditions of flow field boundary were $Ma = 0.6$, $Re = 2.32 \times 10^6$, $\rho = 1.23 \text{ kg/m}^3$, $T_\infty = 288.15 \text{ K}$ and $P_\infty = 1.01325 \times 10^5 \text{ Pa}$. The structural material properties for the wing and main body were $E_1 = 0.89 \text{ GPa}$, $E_2 = 1.54 \text{ GPa}$, $\nu = 0.31$, $G = 2.6 \text{ GPa}$, $\rho_1 = 381.98 \text{ kg/m}^3$; Where $E_1$ and $E_2$ 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 flow field of the model was generated by polyhedral mesh, and the structure of the main wing was generated by tetrahedral mesh. The number of flow field mesh and structure mesh is 3 million and 800 000, respectively.

4. Aerodynamic characteristic

The aerodynamic characteristics of the canard-FSW configuration and the bending-torsion deformation of the canard-FSW at different canard heights were analyzed.

Compared with the FSW model without canard (F01), the longitudinal aerodynamic characteristics of the rigid and elastic canard-FSW models were calculated.

(a) Lift coefficient  (b) Drag coefficient  (c) Lift-drag ratio (d) Pitching moment coefficient

Figure 3. Aerodynamic characteristics of elastic and rigid models

It could be seen from the Figure 3(a) that, compared with F01, the lift coefficients of the canard-FSW models under rigid and elastic conditions were significantly increased by about 30%. The lift line slope of the rigid wing changed little, and the lift line slope of the elastic wing decreased gradually, leading to the high lift coefficient of the elastic wing at small angle of attack. With the increase of the angle of attack, the lift coefficient of the rigid wing was higher than that of the elastic wing, and the positions where the lift coefficients intersect were in the range of 10 degrees to 12 degrees. For canard-FSW models, the lift coefficient of the high wing was higher than that of the low wing in both elastic and rigid states. The lift coefficient of the C-F11 model was about 10% higher than that of that of C-F13 model.

As shown in Figure 3(b), the drag coefficient of the canard-FSW model was larger than that of F01 model, which shows that the drag coefficient of the canard-forward swept wing increased with the increase of the angle of attack, and the drag coefficient of the elastic wing increased significantly compared with the rigid wing. The drag coefficient of FSW11 model was about 11% higher than that of FSW13 model under the condition of elastic wing. This was because the canard wing increases the windward area, and the windward area of the high-position canard wing model was also higher than that of the low-position canard wing model.
From the Figure 3(c), the lift-drag efficiency of the elastic wing was better than that of the rigid wing at small angles of attack, but at that time, the lift-drag efficiency of the rigid wing was much better than that of the elastic wing. The maximum lift-drag ratio of the elastic wing was about 22% lower than that of the rigid wing. The angle of attack to achieve the maximum lift-drag ratio was advanced by about 2 degrees. The lift-drag efficiency of canard-FSW models was slightly higher than that of F01 model. The maximum lift-drag ratio was increased by about 7% in the rigid state. The maximum lift-drag ratio of the F01 model was slightly higher in the elastic state, but the canard-FSW model was superior to the F01 model in the full angle of attack.

From the Figure 3(d), the pitching moment coefficient of the canard-FSW model were lower than that of the F01 model. The main wing was placed behind the torque reference point and the canard was placed before the reference point. The lift provided by the canard was used to increase the lifting moment, thus counteracting the torque provided by the main wing.

5. Elastic deformation characteristics

The diagrams of elastic deformation of different canard height models under the conditions of $Ma = 0.6$ and $Re = 2.32 \times 10^5$ were given. It could be seen from the Figure 4 that the torsional deformation and bending deformation of the main wing could be effectively reduced by adding canard to the forward-swept wing model aircraft.

![Figure 4. Elastic deformation contour of models when $\alpha = 4^\circ$](image)

![Figure 5. Variations of displacement and torsional angle of wingtip with angle of attack](image)
The calculated displacement and torsional angle of wingtip varied with the angle of attack under different canard wing models were shown in Figure 5. When \( \alpha < 6^\circ \), the influence of the canard on the elastic deflection was very small; when \( \alpha > 6^\circ \), displacement of wingtip of different models showed different changes, and the canard-FSW reduced the displacement of wingtip by about 6%-8%. For different canard-FSW models, displacement and torsional angle of wingtip of C-F11 model were larger than those of C-F12 and C-F13 models, but the difference was not significant. At high angles of attack, the displacement and torsional angle of wingtip of the C-F11 model were reduced by about 6.63% and 6.82%, respectively, while those of the FSW13 model were reduced by about 11.28% and 11.49% respectively compared with those of F01 model.

Therefore, the bending and torsional deformations of the main wing were greatly improved when the canard was installed at a small angle of attack. The wing tip deflection and torsion angle of the main wing varied slightly with different canard wing positions. The higher the position was in, the greater the deformation was.

6. Analysis of flow mechanism

According to Figure 6, comparing the spatial streamline distributions of C-F11 rigid forward-swept wing and elastic forward-swept wing at different angles of attack, it could be seen that the elastic deformation of forward-swept wing made the upper surface flow characteristics worse. When \( \alpha = 4^\circ \), the streamline on the upper surface of the rigid forward-swept wing did not appear obvious air separation, and the air flow was mainly in the state of attachment. In the elastic state, the streamline on the leading edge of the upper surface of the forward-swept wing was separated, and the flow convolution formed a vortex, which gradually diffused to the wing root and caused the flow velocity to drop. When \( \alpha = 12^\circ \), whirlpools appeared on the upper surfaces of both rigid and elastic wings, but the strength of whirlpools was greater under elastic conditions. The control range of vortex basically covered the entire upper surface of the forward swept wing. At the same time, the swirl of the main wing had an obvious upwash effect on the canard, resulting in the streamlines convolution on the upper surface of the canard. The vortex generated by the canard was pushed outward by the vortex generated by the forward wing, which affected the control of the canard vortex on the upper surface of the forward swept wing.

![Figure 6. Streamline distributions of C-F11 model](image)

7. Conclusion

Based on CFD/CSD loosely coupled algorithm, the static aeroelastic characteristics of different canard height models were analyzed. The results showed that:
1) The canard coupled forward-swept wing model could effectively improve the aerodynamic characteristics of the forward swept wing and delayed the stall of the main wing.

2) Compared with C-F12 and C-F13 models, the aerodynamic characteristics and elastic deformation characteristics of the C-F11 models were improved better. The detached vortices generated by the high canard could effectively enhance the strength of the main wing vortices and improve the root stall of the forward swept wing.

References
[1] Breitsamter C, Laschka B. Vortical flowfield structure at forward swept-wing configurations. Journal of Aircraft, 2001, 38 (2): 193-207.
[2] Zhang B Q, LASCHKA B. On forward-swept wing's aerodynamic characteristics [J]. Journal of Northwestern Poly technical University, 1989, 7 (3): 321-328.
[3] Wang Jin-jun, Zhao Xia, Wang Shuangfeng, et al. Experimental investigation on longitudinal aerodynamic characteristics of Canard-Forward-Swept wing configuration. Acta Aerodynamica Sinica, 2004; 22 (2): 237-240.
[4] Ren Zhi-jing, Wang Xu, Liu Wen-fa. Numerical Simulation on Aerodynamic Influence of Canard on Forward-swept Configuration. Acta Aeronautica et Astronautica Sinica, 2010; 31 (7): 1318-1323.
[5] Chen Da-wei, Yang Guo-wei. Static aeroelastic analysis of a flying-wing using different models. Chinese Journal of Theoretical and Applied Mechanics, 2009; 41 (4): 469-479.
[6] Fang Bao-ru. Aircraft aerodynamic configuration design. Beijing: Aviation Industry Press, 1997.
[7] Feng Hao-yang, Su Xin-bing, Ma Bin-lin, et al. Static Aero-elastic Computation with Polyhedron Grid. Flight Dynamics, 2016; 34 (4): 24-28.
[8] Liu Y, Bai J Q, Hua J, et al. A high-fidelity static aeroelastic analysis method for complex configuration and its application [J]. Journal of Northwestern Polytechnical University, 2015, 33 (1): 14-20.
[9] Gumerov N A, DURAIWAMI R. Fast radial basis function interpolation via preconditioned Krylov iteration [J]. SIAM Journal on Scientific Computing, 2007, 29 (5): 1876-1899.
[10] Ballmann J, DSafnis A, Korsch H, et al. Experimental Analysis of High Reynolds Number Aero-Structural Dynamics in ETW [C]// The 46th AIAA Aerospace Sciences Meeting. Reno, Nevada: AIAA, 2008, 841: 7-10.