Static Aeroelastic Research of Supersonic Wing

Sen Mao, Qiang Guo, Wenliang Feng, Lixia Zhao and Bin Chen
Chengdu Aircraft Industry (Group) Co., LTD., Chengdu, China

Abstract. The thin airfoil design and the supersonic flight condition make the aeroelastic deformation have an important effect on the aerodynamic characteristics of the supersonic aircraft. In this paper, a supersonic Unmanned Aerial Vehicle (UAV) wing is taken as the research object, and the static aeroelastic weak coupling calculation method (CFD/CSD) is used to carry out the modification of the aerodynamic coefficient of the wing. The analysis results show that the aeroelastic deformation reduces the lift coefficient, and the pitch moment produces a head-up increment. At the same time, the aerodynamic focus of the wing moves forward, which reduces the static stability margin of the aircraft. The influence of aeroelastic deformation on aerodynamic characteristics increases with increasing Mach number.

Keywords: supersonic wing; Static aeroelasticity; CFD/CSD coupling; Aerodynamic characteristics.

1. Introduction

Supersonic flight capability is one of the development directions of future UAVs. In order to meet the requirements of supersonic flight under the condition of limited cross-sectional thrust, most aircrafts adopt thin airfoil with a relative thickness of 3%~5%. The deformation of such wing structure design is relatively significant under large overload. On the other hand, the crossing from subsonic to supersonic will cause significant changes in aerodynamic force. Therefore, it is very necessary to carry out static aeroelastic correction for supersonic aircraft aerodynamic data [1, 2, 3], so as to ensure the accuracy of flight performance, quality and load.

The current static elastic correction is indirectly obtained by obtaining the aerodynamic force and deformation of the aircraft after deformation. There are three methods to obtain static aeroelastic correction: numerical simulation, wind tunnel test and flight test. Wind tunnel test is the most accurate method, but it needs to design and manufacture the elastic scale model and carry out the wind tunnel test, which has a long period and high cost. Flight test requires attaching strain gauge to real aircraft to obtain deformation in flight, and its aerodynamic load is difficult to obtain accurately. Numerical simulation has the advantages of fast speed and high accuracy, and is widely used in the early stage of scheme design. The classical numerical analysis method of static aeroelasticity mainly adopts the lifting surface theory, such as the 144 module of commercial software MSC. However, this method adopts the flat plate aerodynamic method and cannot consider the airfoil effect. With the progress of computer technology, the methods of coupled computational fluid dynamics (CFD) and computational structural dynamics (CSD) to solve aeroelastic problems have been developed rapidly [4]. The coupling methods of CFD and CSD include strong coupling method and weak coupling method. The strong coupling method combines the reconstruction of fluid and structural equations into a new set of equations, which can be solved simultaneously over time [5]. However, it is difficult to construct and solve the same equation, which is generally limited to two-dimensional problems and difficult to be used in engineering practice. The weakly coupled method is used to solve the fluid domain and the solid domain respectively. The disadvantage of weak coupling is that there is a time lag problem, and the time accuracy is only one order. For the solution of this paper's static aeroelastic problem, it only cares about the final static aeroelastic convergence results, and does not require accurate time-domain response history, so the weak coupling method is adopted in this paper.

In this paper, the wing of a supersonic UAV is taken as the research object, and the static aeroelastic correction of aerodynamic coefficient is carried out by using the weakly coupled processing method, so as to provide theoretical support for the aerodynamic design of supersonic UAV.

2. Simulation calculation method

The flow of CFD/CSD static aeroelastic analysis adopted in this paper is shown in Figure 1.

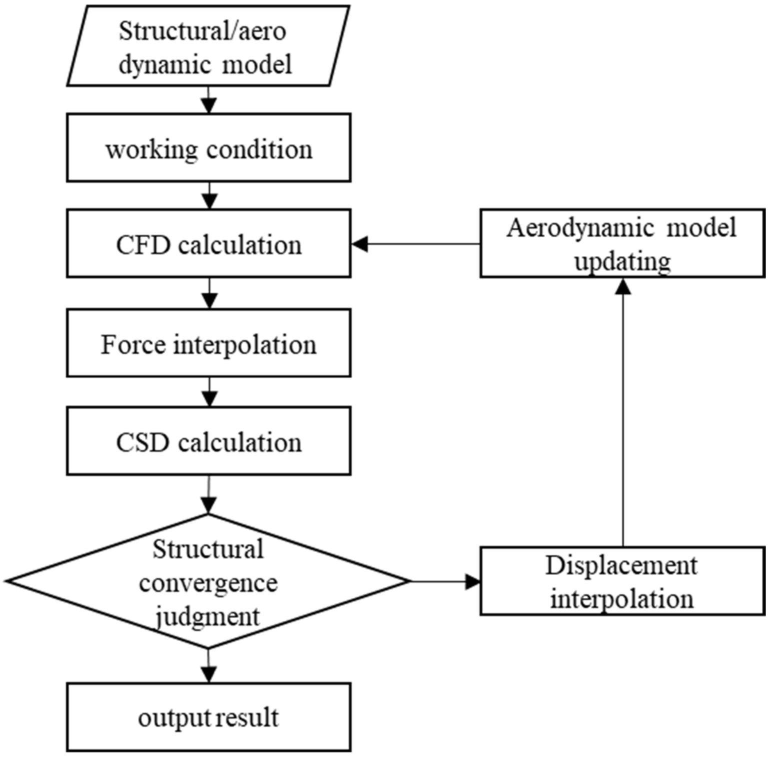


Figure 1. Static aeroelastic calculation process.

Step 1: Based on the initial wing, the finite element model of aerodynamic shape and structure is established;

Step 2: Given the working conditions, solve the CFD aerodynamic equation to get the distributed aerodynamic force of the wing surface;

Step 3: Interpolate the distributed aerodynamic forces into the nodes of the finite element model

Step 4: Calculate CSD structural equation to obtain structural deformation;

Step 5: Interpolate the structural deformation onto the aerodynamic mesh to generate the wing configuration after deformation;

Step 6: Judge whether the calculation converges according to the calculation results of two adjacent times. If so, the calculation is over. If no, repeat Steps 2-5 until the system converges.

3. wing model

The wing consists of the main wing surface, aileron and wing tip. The main wing surface is composed of beams and frame as the structural skeleton. The wing tip adopts sandwich composite material structure, the upper and lower skin is carbon fiber laminate, and the middle is full height foam sandwich. MSC. Patran/Nastran was used for structural finite element design and strength check. The finite element structure is shown in Figure 2.

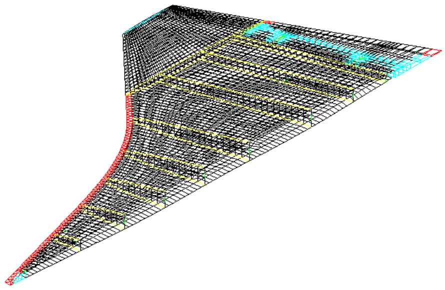


Figure 2. Finite element model of the wing.

The circular head airfoil is suitable for supersonic flight with relatively small thickness, with relative thickness of 3.5% and relative camber of 0.22%.

CFD module adopts MGAERO solver based on Euler equation. The aerodynamic model is composed of surface grids and spatial Cartesian grids. The Cartesian grids are divided into 6 layers and the total number of grids is 10,201. The aerodynamic model is shown in Figure 3.

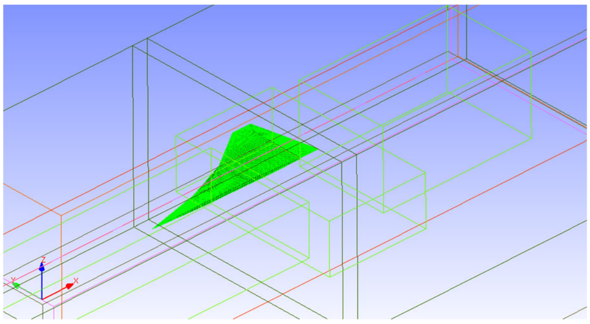


Figure 3. Aerodynamic mesh.

In finite element calculation, the wing root is fixed [6]. The fluid-structure coupling form is a bidirectional weakly coupled form of displacement and force. Thin plate spline method (TPS) is used for data interpolation [7], and the interpolation function is as follows:

$$\Phi(x) = c + a^T x + w^T s(x) \tag{1}$$

c is the coordinate of the control point, and a, w are the weight vectors,

$$s(x) = \left(\sigma(x - x_1), \sigma(x - x_2), \cdots, \sigma(x - x_N)\right)^T, \quad \sigma(x) = \|x\|_2^2 \log \|x\|_2 .$$

4. Result and Analysis

In order to study the influence of static aeroelastic deformation on longitudinal aerodynamic coefficient, lateral-directional aerodynamic coefficient and aileron efficiency, various working conditions were constructed as shown in Table 1, with the speed span ranging from low Mach number to supersonic speed.

Table 1. working condition.

working condition	Mach number	Angle of attack (º)	angle of sideslip (º)	Aileron deflection Angle (º)	Altitude (km)
longitudinal	0.4~1.2	0~8	0	0	0~10
lateral-directional	0.4~1.2	0	-6~6	0	0~10
aileron efficiency	0.4~1.2	0	0	-10~10	0~10

4.1 Longitudinal result

The wing deformation is shown in Figure 4 under the condition of M0.8 and angle of attack 4°. Under aerodynamic action, the wing appears reverse, and the deformation increases with the increase of the angle of attack and Mach number. The maximum deformation of the wing tip under all working conditions is 0.699% CA (chord length of average aerodynamic), which can be seen that the wing stiffness is high. On the other hand, it can be seen that there is a negative torsion in the outer wing segment, and the torsion Angle also increases with the increase of the angle of attack and Mach number. The maximum torsion angle of the wing tip is -0.091°. The deformation results show that the deformation of the wing beam is smaller than that of the skin.

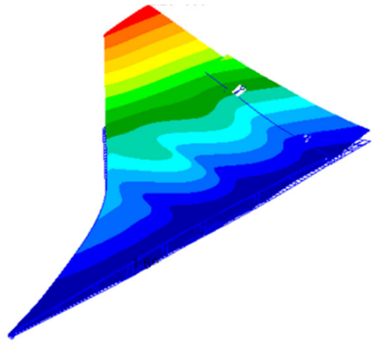


Figure 4. Wing deformation.

Figure. 5 shows the calculation results of static aerodynamic elasticity of the wing aerodynamic focus. The rigid results show that with the increase of Mach number, the aerodynamic focus shifts backward. The main reason is that the minimum drag changes little at subsonic speed and increases significantly at supersonic speed. When Ma=1.4, the aerodynamic focus shifts backward by about 20%cA. After considering the aeroelastic deformation, the aerodynamic focus moves forward. The main reason is that the negative torsion of the wing causes the change of aerodynamic distribution, which is reflected in the decrease of aerodynamic force outside the wing. With the increase of Mach number, the deformation increases and the forward movement of the focus increases. When the Mach number is 1.4, the forward movement of the pneumatic focus is about 4.75%CA.

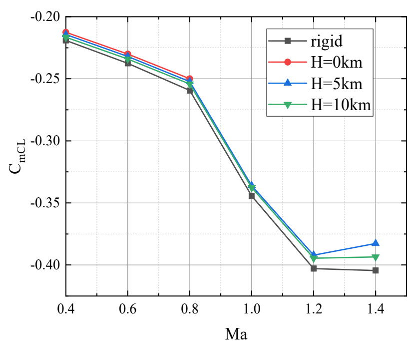


Figure 5. Static aeroelastic simulation results of wing aerodynamic focus.

Static aeroelastic simulation results of lift curve slope are shown in Figure 6, and the rigid results show that the lift coefficient varies monotonically at all velocities. It can be seen that the lift curve slope decreases by about 0.84%~8.14%, mainly because the static aeroelastic deformation brings negative torsion of the outer wing segment, and the local angle of attack decreases. With the increase of the angle of attack and Mach number, the deformation increases and the slope decreases.

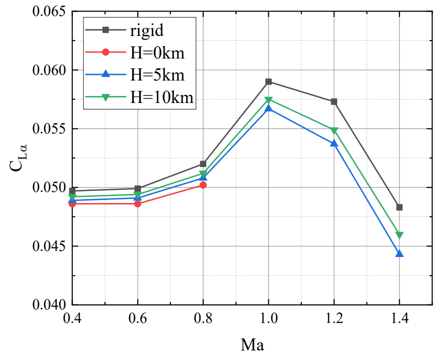


Figure 6. Static aeroelastic simulation results of lift curve slope.

The simulation results of zero lift moment coefficient and zero-lift angle are shown in Figure. 7 and Figure. 8. It can be seen from the results that the zero lift pitching moment coefficient has a small increment and the zero-lift angle increases positively. This is due to the negative torsion of the outer segment of the wing, resulting in changes in aerodynamic torque.

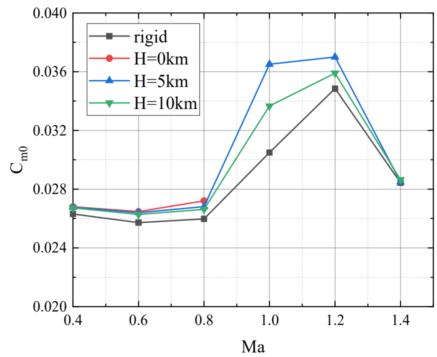


Figure 7. Static aeroelastic simulation results of zero lift moment coefficient.

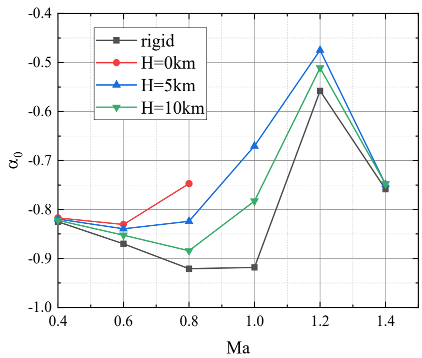
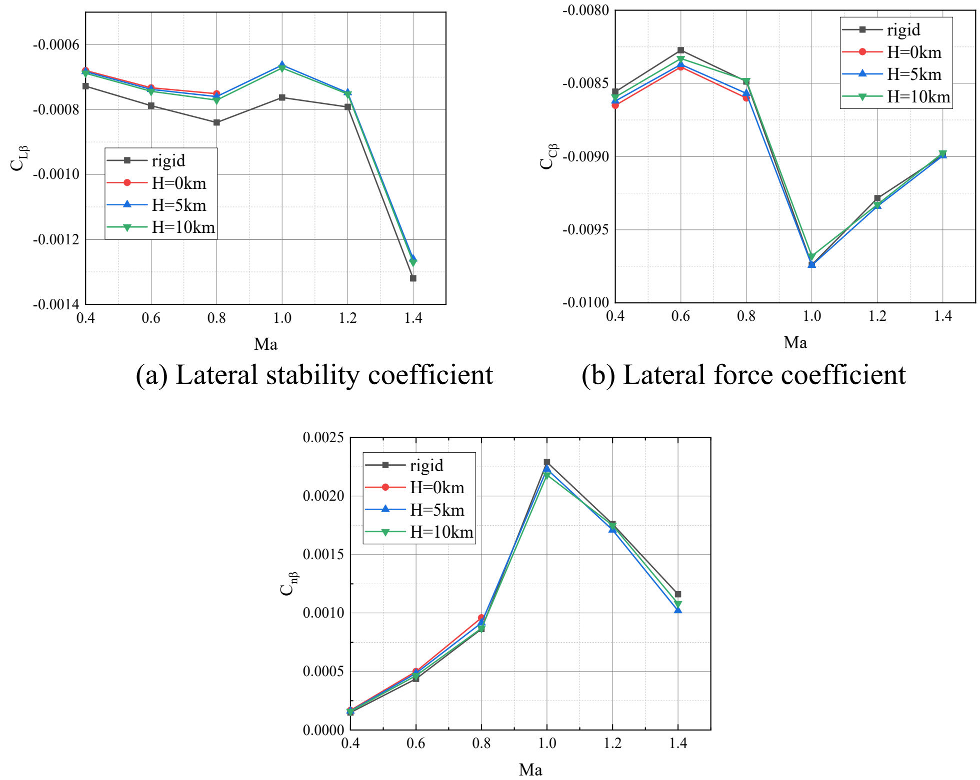


Figure 8. Static aeroelastic simulation results of zero-lift angle.

4.2 lateral-directional result

Figure. 9 shows the static aeroelastic simulation results of lateral-directional aerodynamic coefficient. The rigid results show that the yaw moment coefficient and roll moment coefficient do not cross or reverse in the range of attack angles and sideslip angles calculated by each Mach number, and the range of lateral stability and course stability is large.

The results of aeroelastic calculation show that the lateral stability decreases, with the maximum correction of 13% (Ma=1.2, H=5km) for two reasons. On the one hand, aircraft with small aspect ratio generally have better spanwise stiffness. The wing deflection deformation is small, and the lateral stability increment caused by deformation is limited. On the other hand, negative wing torsion causes the lateral lift contribution to decrease and aerodynamic pressure center to move inward. At the same time, negative torsion also reduces lift coefficient, resulting in overall transverse stability reduction. The lateral force coefficient and course stability increase at subsonic and decrease at supersonic.



(a) Lateral stability coefficient (b) Lateral force coefficient

(c) directional stability coefficient

Figure 9. Static aeroelastic simulation results of lateral-directional coefficient.

4.3 Aileron efficiency

Static aeroelastic simulation results of aileron efficiency (single right-sided aileron, positive trailing edge downward) are shown in Figure 10. The coefficient of rolling moment changes monotonically without aileron reversal. Considering that the aileron efficiency decreases after aerodynamic deformation, the reduction range increases with the increase of aerodynamic pressure, and C_{lda} decreases by about 40% under the high aerodynamic condition (M=0.8, H=0km). The reason for the large decline in aileron efficiency is that aileron deformation is larger than the deformation of the wing, which can be seen from the static aeroelastic structure deformation of aileron (M=0.8, H=10km, aileron deflects 10°), as shown in Figure 11.

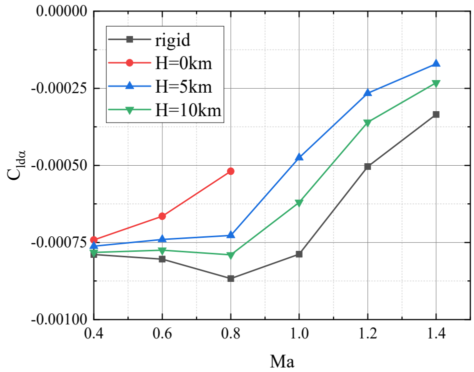


Figure 10. Static aeroelastic simulation results of Aileron efficiency.

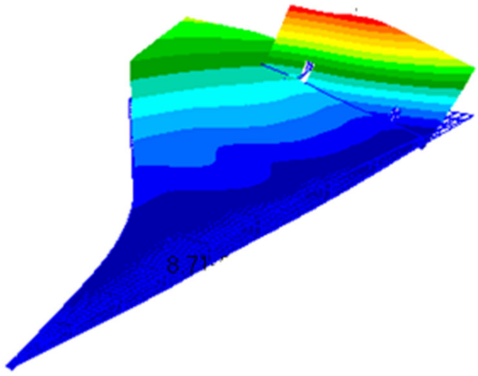


Figure 11. Static aeroelastic deformation of ailerons

5. Conclusion

In this paper, CFD/CSD static aeroelastic coupling method is used to analyze the influence of aeroelastic deformation on aerodynamic characteristics of a supersonic wing. The conclusions are as follows:

(1) After aeroelastic deformation, the wing has upward bending deformation and negative torsion angle, which reduces the effective angle of attack, and thus the lift curve slope decreases slightly.

(2) The pitching moment increases positively after the aeroelastic deformation, which is equivalent to increasing a head-up moment, and the zero lift moment coefficient decreases by 0.001~0.031. At the same time, the aerodynamic focus moves forward considering the static aeroelastic effect. When the Mach number is 1.4, the aerodynamic focus moves forward about 4.75%CA.

(3) The modified lateral stability is slightly lower and the course stability is almost constant considering the static aeroelastic effect.

In conclusion, the wing aerodynamic characteristics change significantly after aeroelastic deformation. Therefore it is necessary to consider the static aeroelasticity in the design stage of supersonic UAV.

References

[1] Yong Lu, Pan Cheng, Xiaoyan Liu. Static aeroelastic Correction of Wing Profile Based on CFD Method [J]. Science and Technology Information, 2013(18):2.

[2] Ruijun Fan, Zhaohui Feng, Zhou Zhou. Calculation and Analysis of Static aeroelastic Problem of High Aspect Ratio UAV [J]. Quarterly Journal of Mechanics, 2009,30 (4) : 548-554.

[3] Snyder R , Hur J Y , Strong D , et al. Aeroelastic Analysis of a High-Altitude Long-Endurance Joined-Wing Aircraft[C]// 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. 2005.

[4] Xiaomin An, Min Xu, Shilu Chen. Research Review of Nonlinear Aeroelasticity solved by Multi-field Coupling [J]. Advances in Mechanics, 2009,39 (3) : 284-298.

[5] Tienne S, Pelletier D, Garon A. A Monolithic Formulation for Steady-State Fluid-Structure Interaction Problems [R]. AIAA-2004-2239.

[6] Zhaotao Chen, Qin Sun. Application of Inertia Release in Static Aeroelastic Simulation of Aircraft [J]. Journal of Flight Mechanics, 2008,26 (5) : 71-74.

[7] Powell, M.J.D.. The theory of radial basis function approximation in 1990. Advances in Numerical Analysis, Oxford, Clarendon Press,1992.