Numerical simulation of support interference characteristics on a low-aspect ratio flying-wing model

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Abstract. The flying-wing aircraft is a promising concept for the mid or long-term commercial aviation due to its excellent performance in aerodynamic and structure, which has been studied by a number of investigators both experimentally and computationally. However, the conditions in wind-tunnel testing do not necessarily reflect those observed in free flight, the support structure interference is an important factor to affect experimental data collected from wind tunnels. Support interference characteristics of a flying-wing model from subsonic to supersonic speed is investigated by numerical simulation methods. Results show that grid convergence is obtained with the series of grids, which implies that the solutions are in the asymptotic range. The support has a relatively small effect on aerodynamic characteristics of flying-wing aircraft at low speed while has a relatively large effect on drag at transonic speed and supersonic speed.

1. Introduction
The flying-wing aircraft is a promising concept for the mid long-term commercial aviation due to its excellent performance in aerodynamic and structure, and it has been successfully used in B-2 bomber, X-37 aircraft and many advanced unmanned aerial vehicles [1-3]. It’s necessary to research the aerodynamic characteristics of flying-wing aircraft. A low-aspect-ratio flying-wing model is created to investigated the aerodynamic characteristics of flying-wing aircraft [4].

It’s essential to carry out high speed wind tunnel tests for the low-aspect-ratio flying-wing model. However, the condition in wind-tunnel testing do not necessarily reflect those observed in free flight, the support structure interference is an important factor to affect experimental data collected from wind tunnels [5-7], and the support interference of flying-wing aircraft is different from normal aircraft because of its specific configuration. Support interference characteristics of a flying-wing model from subsonic to supersonic speed is investigated by numerical simulation methods in this paper.

2. Numerical Method
2.1. MFlow software
The computations here were conducted by using the China Aerodynamics Research & Development Center (CARDC) MFlow-code [8, 9], which is an finite volume cell-center CFD solver and has participated in the 5th and 6th CFD drag prediction workshop [10], the MFlow software behaved as good as other famous international CFD software(seeing Fig. 1). Second-order accuracy in space is
achieved by linear reconstruction in cells. The vertex-based Gauss method is used for gradient computations, to simultaneously fulfill accuracy and robustness. Roe scheme [11] is used for inviscid flux computations, and the Venkatakrishnan limiter [12] is used to restrict oscillation.

Figure 1. 5th AIAA CFD drag prediction workshop

2.2. Geometry and Computational Grids

The aerodynamic characteristics of the low-aspect-ratio flying-wing model from subsonic to supersonic speed should be investigated, so the wind tunnel tests would be carried out in different subsonic and supersonic wind tunnels, and a low-speed wind tunnel model and a high-speed model are taken into the investigation of support interference. There are 3 configurations of low-aspect-ratio flying-wing model: low speed wind tunnel model, high speed wind tunnel model and the configuration of real aircraft (seeing Fig. 2).

(a) low speed model  (b) high speed model  (c) real model

Figure 2. Computational geometry

Mesh generation is the basis of numerical simulation, the computational grid is structured grid and is designed by 3 levels. First level is boundary grids which is used to simulated the viscous flow, second level is fine grids to simulated special aerodynamic characteristics such as shocks and vortexes, and the third level grid satisfies the far field boundary conditions. Fig. 3 shows the topology of structured grid.

Figure 3. Grid topology
3. Results and Discussion

3.1. Grid convergence study

A series of 4 nested structured grids of low speed model and real model are adopted for grid convergence study (see Fig. 4), the numbers of grid cells are 392K, 1414K, 4429K and 14116K respectively. The grids of low speed model are the same as real model without support except the grids of support. And the aerodynamic forces presented in this paper do not include the support.

![Grids for grid convergence study](image)

Figure 4. Grids for grid convergence study

Fig. 5 and Fig. 6 show the convergence curve of lift, drag and pitch moment, “zhg” in the figure means the aerodynamic forces with support, and “zhshht” in the figure means the aerodynamic forces without support. The horizontal coordinate stands for $N^{2/3}$, where $N$ is the total cell number. The solver is designed to achieve 2nd order accuracy in space, therefore $N^{2/3}$ stands for the square of typical cell scale for a series of nested grids. If the solver is correctly established and the grid series is located among the asymptotic range of convergence the force and moment should display linear behavior in the grid convergence curves. It can be seen that the coarse grid, medium grid and fine grid achieve the grid convergence.

![Grid convergence plots at Ma=0.2, $\alpha$=6](image)

Figure 5. Grid convergence plots at $Ma=0.2$, $\alpha=6$
The converged solution can be obtained by interpolation of the different grids, and Table 1 shows the convergence results of lift, drag and pitch moment. It can be seen that the solution of medium grid and fine grid are very close the converged solution.

| Grid Type     | CL    | ΔCL  | CD   | ΔCD  | Cm  | ΔCm  | n²³(10⁻⁵) |
|---------------|-------|------|------|------|-----|------|------------|
| Extracoarse   | 0.23779 | -0.00052 | 0.02412 | 0.00162 | -0.03324 | -0.00010 | 18.7       |
| Coarse        | 0.23987 | 0.00156 | 0.02454 | 0.00204 | -0.03385 | -0.00071 | 7.9        |
| Medium        | 0.23911 | 0.00080 | 0.02389 | 0.00139 | -0.03351 | -0.00037 | 3.7        |
| Fine          | 0.23868 | 0.00037 | 0.02314 | 0.00064 | -0.03331 | -0.00017 | 1.7        |
| Interpolation | 0.23831 | 0.02250 | -0.03314 | 0.00000 | 18.7 |

3.2. Support Interference study

The support interference of flying-wing aircraft can be investigated by comparison of wind tunnel model with support and real model without support. According to the grid convergence study the fine mesh is used in the numerical simulation.

Fig. 7 shows the support interference at Ma=0.2, 0.95 and 1.5, it can be seen that when attack angle is small (Ma=0.2, α<28° or Ma=0.95, α<8°), the support reduces the lift, and the support interference decreases with the increase of attack angle. Also, the support would reduce the drag, and the support interference increases with the increase of attack angle. And the support magnifies the pitch moment when attack angle is small.
Table 2. Aerodynamic coefficient dispersion for support bracket disturbance at α=4°

| Ma  | ΔCL  | %   | ΔCD  | %   | ΔCm | %   |
|-----|------|-----|------|-----|-----|-----|
| 0.2 | -0.01054 | 6.2 | -0.00048 | 3.0 | 0.00112 | 4.4 |
| 0.95 | -0.00551 | 2.5 | -0.00321 | 12.5 | 0.00352 | 6.7 |
| 1.5 | -0.00466 | 2.7 | -0.00411 | 11.6 | 0.00202 | 4.4 |

Table 2 shows the aerodynamic coefficient dispersion for support bracket disturbance at α=4°, it can be seen that the support has a large influence on lift while has a small influence on drag, even less than 5 counts. On the contrary, the support affects the drag more at Ma=0.9 and Ma=1.5, about 45 counts (12%), while has a less effects on lift (2.5%).

Fig. 8 and Fig. 9 show the streamline and pressure distribution at Ma=0.2, α=0°and α=36°. When α=0°, the support increases the pressure of the upper surface at tail, so that decreases the lift, and the tail is located in the protected area so that the drag and pitch moment increase compared with the flying-wing model without support. On the contrary, when α=36° there is a high-pressure area at tail without support and the support decreases the pressure of the upper surface at tail, so that increase the lift and decrease the pitch moment. The surface streamline and pressure distribution are well coincident with the aerodynamic coefficient.

Figure 8. Surface streamline and pressure distribution at Ma=0.2, α=0°

Figure 9. Surface streamline and pressure distribution at Ma=0.2, α=36°

Fig. 10 and Fig. 11 show the streamline and pressure distribution at Ma=0.95, Ma=1.5, α=0°. It can be seen that there are separated vortexes at the tail of the real model without support, and the separated vortexes at the tail is decreased by the support, which increase the drag.
4. Conclusion
Numerical investigations of low-aspect-ratio flying-wing aircraft benchmark model are performed with in-house solver MFlow. The grid convergence study and support interference study are presented in this paper:

1. Grid convergence is obtained with the series of grids, which implies that the solutions are in the asymptotic range.
2. The support has a relatively small effect on aerodynamic characteristics of flying-wing aircraft at low speed.
3. The support has a relatively large effect on drag of flying-wing aircraft at transonic speed and supersonic speed, while has a relatively small effect on lift and pitch moment.

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