Electronic supplementary materials
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Design and aerodynamic performance of a wide-speed-range morphing aircraft with horizontal takeoff

Xu ZHANG[1], Binbin YAN[2], Heng ZHANG[3], Yunfei ZHANG[4], Shuangxi LIU[5], Wei HUANG[5]

[1]*Unmanned System Research Institute, Northwestern Polytechnical University, Xi'an 710072, China*
[2]*School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China*
[3]*School of Aerospace Engineering, Tsinghua University, Beijing 100084, China*
[4]*Shanghai Hangdi Technology Co., Ltd., Shanghai 201818, China*
[5]*Advanced Propulsion Laboratory, National University of Defense Technology, Changsha 410073, China*

S1 Code validation

To verify the accuracy of the numerical simulation method, wind tunnel test data for two vehicle models were selected as a reference. Comparison data at subsonic and hypersonic speeds are from wind tunnel tests of DLR-F6 WB and AGARD-B, respectively.

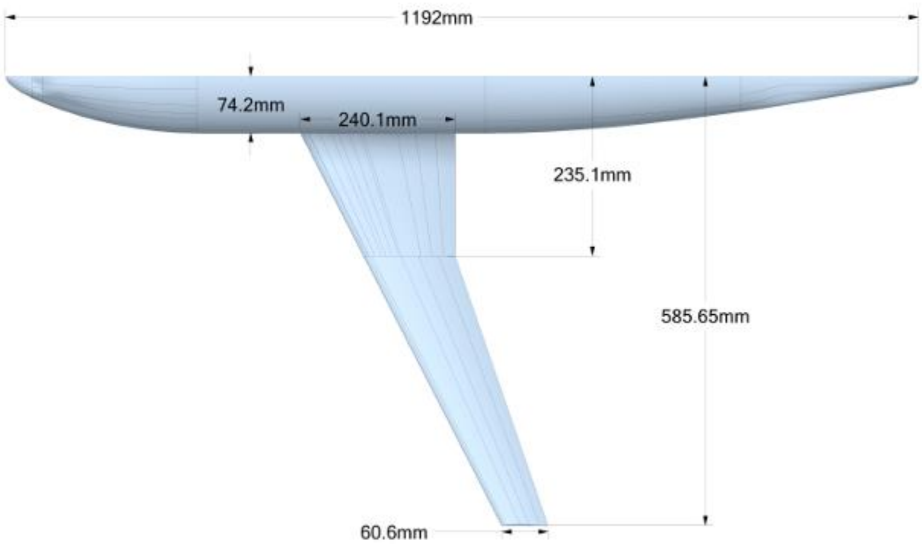


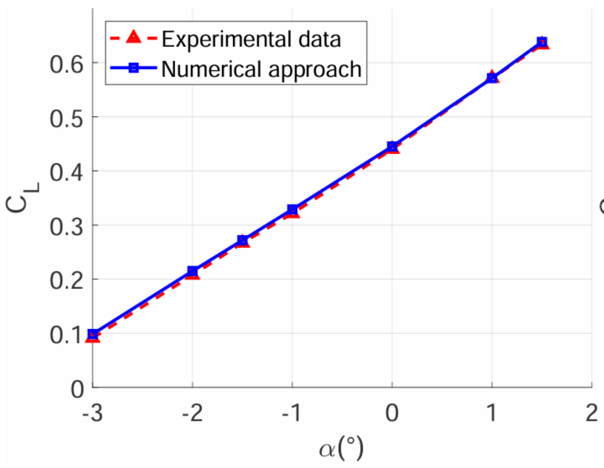
Fig. S1: Main dimensions of the DLR-F6 WB configuration

S1.1 DLR-F6 at Ma = 0.75

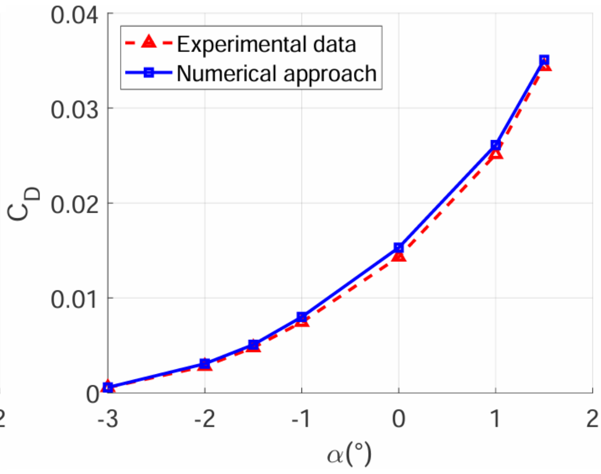
The primary parameters of the DLR-F6 WB configuration are shown in Fig. S1. The DLR-F6 wing-body assembly configuration designed by the German Aerospace Academy (DLR) was the study model chosen for the DPW II and DPW III workshops Clark et al. (2012); Laflin et al. (2005). Experimental measurements of the configuration were carried out in the S2MA wind tunnel at the Office National d' Etudes et de Recherches Aerospatiales (ONERA) in France. The influence of different factors (turbulence model, turning model and viscous model) on the drag calculation was investigated using the CLF3D and OVERFLOW software platforms by NASA and Langley Centre Sclafani et al. (2014). The lift coefficient and drag coefficient of the DLR-F6 WB were calculated by the numerical simulation method, and the comparison of them with the wind tunnel test results are shown in Fig. S2 and Table S1. The maximum error in the lift coefficient for different angles of attack is 8.100%, and the average value of the error is 2.529%. The maximum error in the drag coefficient for different angles of attack is 9.312%, and the average value of the error is 7.867%. The comparison results demonstrate that the calculation approach in this study has enough calculation accuracy in the subsonic speed range.

Table S1: Difference of lift and drag coefficients compared with experimental data at Ma = 0.75

Angle of attack, α (°)	-3	-2	-1.5	-1	0	1	1.5
Difference in lift coefficient (%)	8.100	3.563	1.844	2.299	1.122	-0.001	0.779
Difference in drag coefficient (%)	2.139	9.312	6.323	7.547	6.862	3.910	2.041



(a) Lift coefficients.



(b) Drag coefficients.

Fig. S2: Comparison of numerical and experimental data at the Mach number of 0.75

S1.2 AGARD-B at *Ma* = 5

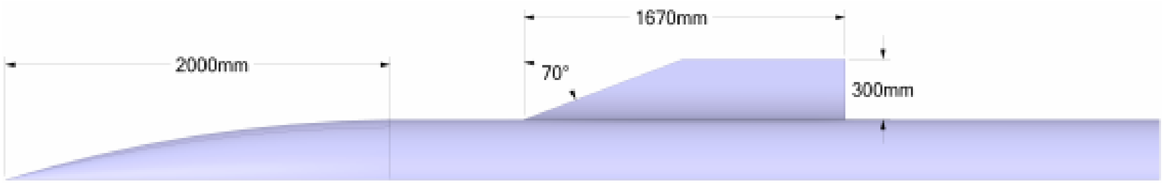
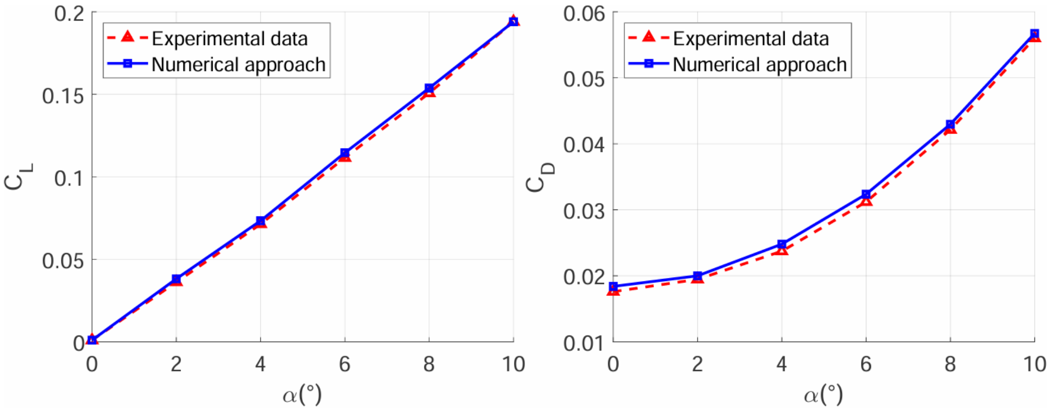


Fig. S3: Main dimensions of the AGARD-B WB configuration

Table S2: Difference of lift and drag coefficients compared with experimental data at Ma = 5

Angle of attack, α ($^\circ$)	0	2	4	6	8	10
Difference in lift coefficient (%)	0.003	5.556	2.817	2.703	1.994	0.002
Difference in drag coefficient (%)	4.546	2.740	4.495	3.419	1.266	0.952



(a) Lift coefficients.

(b) Drag coefficients.

Fig. S4: Comparison of numerical and experimental data at the Mach number of 5

The wind tunnel test model AGARD-B was selected for validation of the hypersonic phase. Fig. S3 depicts the basic dimensions of the AGARD-B vehicle and Fig. S4 compares the AGARD- B test results with the aerodynamic data obtained using numerical methods. The test data and geometrical parameters are referred to in Gjb. (2002). From Fig. S4 and Table S2, it can be seen that the numerical simulation results are in good agreement with the test values. The maximum error in the lift coefficient for different angles of attack is 5.556%, and the average value of the error is 2.179%. The maximum error in the drag coefficient for different angles of attack is 4.546%, and the average value of the error is 2.903%. From the requirement of aerodynamic calculation accuracy, the adopted grid division strategy and calculation method can meet the requirements of the study.

S1.3 Computational grid and grid independence validation

A three-dimensional docked structured grid is used to numerically simulate and assess the flow field condition of the vehicle's aerodynamic configuration. Because the wide-speed range morphing vehicle in this study has an axisymmetric structure, side slip can be ignored in numerical simuations to lower computational effort using half-mode networks. Fig. S5 displays the aerodynamic layout's surface and symmetry mesh in the computational process. An O-shaped topology is used and the flow field space near the walls of the aerodynamic layout is finely divided. Considering the influence of the computational grid on the results, grid-independence validation is required. Three sets of grids are constructed separately, defined as fine, medium and coarse grids. The number of meshes for fine, medium and coarse grids are 17.13 million, 8.28 million and 5.49 million, respectively. Calculating the lift coefficient C_L and drag coefficient C_D of the aerodynamic layout at Mach 6, angle of attack 6° , swept angle of 45° and without considering the sideslip angle, the calculated results of the numerical simulation are shown in Table S3 and Fig. S6. Considering the allocation of computational resources and the accuracy of the calculation results, the medium grid is selected as the computational grid for the wide-speed morphing vehicle.

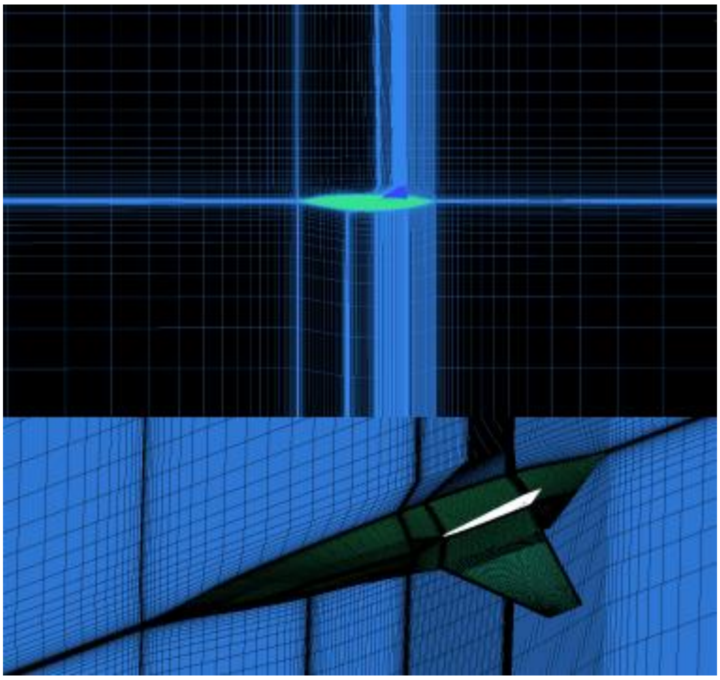
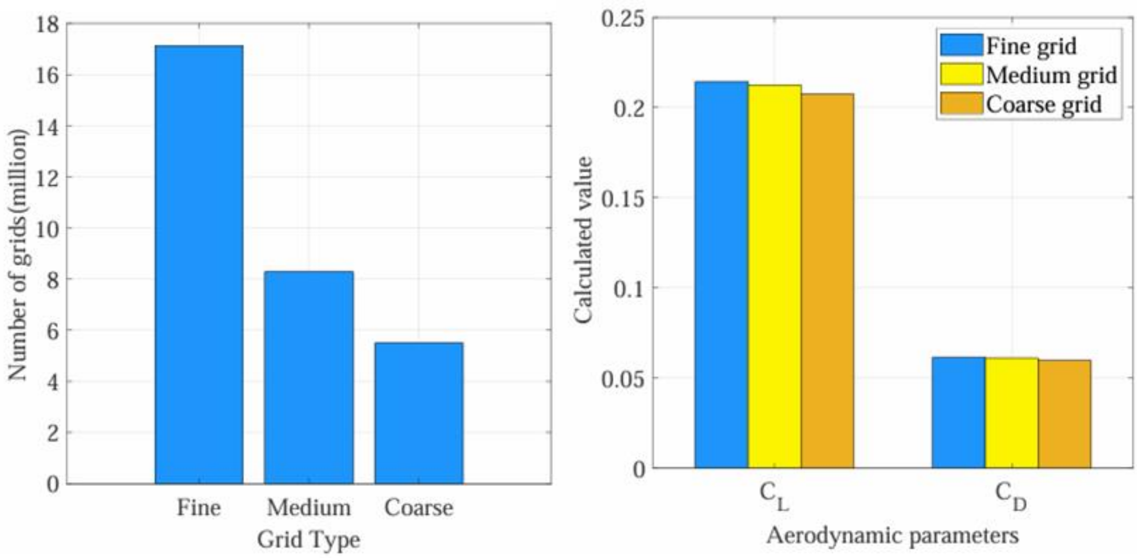


Fig. S5: Computational grids for the hypersonic phase

Table S3: Grid-independent verification

Parameter	Reference value (Fine grid)	Medium grid		Coarse grid	
		Value	Error (%)	Value	Error (%)
C_L	0.214368	212662	0.796	0.207523	3.19
C_D	0.061435	061127	0.501	0.059843	2.59



(a) Comparison of number of grids.

(b) Comparison of calculation results.

Fig. S6: Grid-independence validation bar chart

References

Gjb 4399-2002 hypersonic wind tunnel aerodynamic test method (in Chinese).

Clark C, Kloesel K, Ratnayake N. A Technology Pathway for Airbreathing, Combined-Cycle, Horizontal Space Launch Through SR-71 Based Trajectory Modeling. In: 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference.
https://doi.org/10.2514/6.2011-2229

Laflin KR, Klausmeyer SM, Zickuhr T, et al., 2005. Data summary from second aiaa computational fluid dynamics drag prediction workshop. *Journal ofAircraft*, 42(5):1165-1178.
https://doi.org/10.2514/1.10771

Sclafani AJ, DeHaan MA, Vassberg JC, et al., 2014. Drag prediction for the common research model using cfl3d and overflow. *Journal ofAircraft*, 51(4):1101-1117.
https://doi.org/10.2514/1.C032571