Computational Analysis of Aerodynamic Performance of Mars Airplane

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Flow field and aerodynamic performance of the Mars airplane with a complete aircraft configuration are analyzed by RANS simulations. At the Reynolds number of 3.3×10^4 , a flow field is solved by an unstructured three-dimensional compressible CFD solver (LS-FLOW). Here, the Mars airplane is assumed to have the Ishii airfoil as the main wing shape. The Ishii airfoil is known as its good performance at the low Reynolds number condition. An objective of the present study is to clarify flow structures around a complete aircraft, for optimization of design of the Mars airplane. The results show that the features of the aerodynamic coefficients correspond to those of experimental results and the contribution of the main wing is significant on the aerodynamic characteristics of the entire airplane.

Key Words: Aerodynamic Performance, CFD, Low Reynolds Number, Mars Exploration

Nomenclature

b	: half span of main wing
c	: chord of main wing
C_D	: drag coefficient
c_l	: sectional lift coefficient
C_L	: lift coefficient
C_p	: pressure distribution
L/D	: lift-to-drag ratio
Re	: Reynolds number
α	: angle of attack

1. Introduction

Current and previous missions to Mars have been conducted by ground-based rovers and orbiters. Rovers provide detailed data on the surface but their reach is limited to a small area. On the other hand, orbiting sensors provide spatially wide data but their resolution is very low. There is no approach which has the intermediate role between rovers and orbiters. Thus, the idea of Mars exploration by an airplane has been discussed in JAXA/ISAS for several years.

An airplane design for Mars is very different from the conventional airplanes on Earth. First, the Reynolds number of the flow condition for the Mars airplane is smaller ($Re=10^5$) than the typical airplanes on Earth ($Re=10^7$) because the atmosphere on Mars is much thinner than that on Earth. Second, its cruising Mach number becomes high because the speed of sound on Mars is smaller than that on Earth and the aircraft needs a certain cruising speed to gain sufficient dynamic pressure for lift in the thin atmosphere. Because aircrafts flying in such a flow condition on Earth are limited to high-altitude airplanes, the optimum design of the Mars airplane is not well known.

Kojima et al¹⁾ have showed that thin airfoils are appropriate at the low Reynolds number condition. The Ishii airfoil is one of high performance airfoils. Figure 1 shows the shape of the Ishii airfoil. The Ishii airfoil has several prominent features: (i) the leading edge is round, (ii) the upper surface of airfoil is flat, (iii) the lower surface of airfoil has cambered shape. Two features (ii) and (iii) correspond to the proposition of Schmitz²⁾ for low Reynolds number. Anyoji et al^{3,4)} analyzed the aerodynamic performance of the Ishii airfoil using large eddy simulations (LES). The results show that the Ishii airfoil has a high lift-to-drag ratio in wide range of the angle of attack. Thus, the Ishii airfoil is expected to be a good candidate as the main wing of the Mars airplane.

When an airplane is designed, not only an airfoil itself but also a wing-body configuration should be optimized. Thus, several studies have been conducted to understand effects of a wing-body configuration on its aerodynamic characteristics. However, those studies mainly focus on the high Reynolds number condition, and such effects under the low Reynolds number condition have not been discussed well. The flow field includes several factors, such as a laminar separation bubble, a wing-tip vortex, a wing-body interference and others. Therefore, the flow field might be more complicated than the high Reynolds number condition. The optimum wing-body configuration should be considered and the aerodynamic characteristic should be improved.

In the present study, the flow field with a complete aircraft configuration for the Mars airplane is simulated by Reynolds Averaged Navier-Stokes (RANS) simulations. The simulation result clarifies aerodynamic performance of the current Mars airplane design. An objective of the present study is to evaluate aerodynamic performances of the Mars airplane with varying the angles of attack.

Fig. 1. Shape of Ishii airfoil.

2. Flow Conditions

For the simulation to obtain the aerodynamic coefficient, the angle of attack (α) is changed from 0 to 12 deg at intervals of 2 deg. The Reynolds number (Re) based on the chord length and free stream velocity is set to 3.3×10^4 to compare with the experimental result.⁵⁾ The Mach number is set to 0.2 to ignore the compressibility. Reference 6) shows an effect of the specific heat ratio is negligible in the present Mach number region. Thus, the specific heat ratio is set to 1.4. These conditions are summarized in Table 1.

Figure 2 shows the analysis object. Its dimension is based on the scale model of the Mars airplane used for the experiment.⁵⁾ The real Mars airplane has some propellers for a propulsion system. For simplicity, propellers are abbreviated. The shape of the main wing is the Ishii airfoil with aspect ratio of 5.2. NACA0009 is used as the tail wing. The incident angle of both the main and tail wing is 0 deg.

Table 1. Flow conditions.

Reynolds number	3.3×10^4
Mach number	0.2
Specific heat ratio	1.4

Fig. 2. Analysis object.

3. Numerical Method

3.1. Flow solver

The computational code employed in this study is LS-FLOW: a JAXA's in-house, compressible Navier-Stokes solver for arbitrary polygons. Numerical fluxes for convective terms are evaluated by the SLAU.⁷⁾ The flow field is assumed to be fully turbulent, and the Spalart-Allmaras turbulence model⁸⁾ is applied. Time integration is conducted by using the LU-SGS implicit method.⁹⁾

3.2. Computational grid

An unstructured grid generator called MEGG3D¹⁰⁾ is employed for generation of a grid. Here, MEGG3D is able to generate hybrid grids that consist of elements of tetrahedral, pyramid and prism types.

Figure 3 shows the grid with a complete aircraft configuration for the RANS computation. The grid has approximately 2 million nodes and 6 million elements. Near a surface, an element type is selected to be a prism type. The first element away from the surface is set to be $0.05c/\sqrt{Re}$. The distance from the body surface to the computational outer boundary is $20c$.

Fig. 3. Computational grid.

4. Results and Discussions

4.1. Aerodynamic performances

The aerodynamic force coefficients as functions of α are plotted in Fig. 4. Computational results are compared with the experimental results.⁵⁾ In the two-dimensional airfoil flow simulations performed by LES,^{3,4)} the nonlinear lift curve is observed around $\alpha = 4$ deg. However, the lift curve has a linearity at $\alpha = 0$ to 6 deg in a complete aircraft configuration. The experimental result also shows that the lift curve is linear. Therefore, the current design of the Mars airplane has the linear lift coefficient for a low angle of attack regime. For more than $\alpha = 8$ deg, the lift coefficient is almost constant. The drag coefficient curve has a similar trend to the experimental result.

Although the computational result is slightly different compared with the experimental result, the computational results show a similar trend to the experimental results. Thus, the simulation is assumed to capture the dominant feature of flow structure.

(a) Lift coefficient (C_L)

Fig. 4. Aerodynamic coefficients as function of α .

4.2. Decomposition analysis

Figure 5 shows the half body of the Mars airplane from top view. The surface of the Mars airplane is divided into four panels. In Fig.5, Others represent all the additional objects on the Mars airplane such as sensors. Figure 6 shows the contribution of each panel to lift and drag coefficients, and Table 2 indicates the percentage of the contribution. The lift contribution of the main wing is more than 90% for almost all α . The lift coefficient of the Mars airplane strongly depends on the main wing. The drag contribution of the main wing is more than 60% and it is the most dominant element for all α . Thus, reducing drag of the main wing improves the aerodynamic performance of the Mars airplane. Other panels are almost constant with varying α compared with the drag contribution of the main wing. At $\alpha = 6$ deg (steady flight angle), the drag contribution of all panels excluding the main wing is approximately 24%. Among them, the contributions of the body and tail wing are large. In order to improve the gliding performance, it is necessary to design a low drag body and a tail wing.

Fig. 5. Divided panel list.

Fig. 6. Each panel contribution to aerodynamic coefficients.

Table 2. Component ratio of aerodynamic coefficient.

(a) Lift coefficient [%]				
α [deg.]	Main Wing	Body	Tail	Others
0	101.43	5.12	-6.81	0.26
2	97.21	3.60	-1.02	0.21
4	95.40	3.13	1.29	0.18
6	94.05	3.01	2.78	0.17
8	92.55	3.27	4.02	0.16
10	91.28	3.47	5.06	0.19
12	89.32	3.60	6.83	0.25

(b) Drag coefficient [%]				
α [deg.]	Main Wing	Body	Tail	Others
0	66.31	9.46	21.98	2.25
2	67.99	9.88	19.58	2.55
4	71.38	9.58	16.58	2.46
6	76.03	8.59	13.36	2.03
8	83.31	6.61	8.82	1.26
10	84.96	5.89	8.01	1.13
12	85.20	5.64	8.11	1.05

4.3. Time averaged flow fields

Figure 7 shows an oil-flow image of the main wing. At $\alpha = 0$ deg, flow attaches on the upper surface, but flow separates and reattaches on the lower surface. At $\alpha = 4$ to 6 deg, the separation and reattachment are observed on the upper surface. Flow near a wing-tip is affected by the wing-tip vortex. Especially at $\alpha = 4$ deg, the wing-tip vortex suppresses

Fig. 7. Time averaged surface stream line on the main wing. The lines with notifications S and R indicate the locations of separation and reattachment. The white arrows indicate the flow direction near wall.

separation from near the wing-tip to mid-span. From $\alpha = 8$ to 12 deg, the flow forms the massive separation from the leading edge. This separation and reattachment feature for α corresponds to those of the two-dimensional airfoil flow computed by LES.

4.4. Three-dimensional effects on the main wing

In order to evaluate the three-dimensional effects on the main wing, the pressure coefficient (C_p) distributions on the wing section at $\alpha = 6$ deg (steady flight angle) are plotted in Fig. 8. Figure 8 (a) shows the oil-flow image with the positions of 3 locations. Subsequent figures include the result of the two-dimensional airfoil flow plotted by dash line. Figure 8 (b) presenting C_p close to the body shows the effects of the wing-body interference. The flow separates and reattaches at the trailing edge. The laminar separation bubble is longer than on mid-span. Figure 8 (c) presenting C_p on the mid-span shows a similar trend to the two-dimensional airfoil flow, but the contribution to the lift coefficient from the laminar separation bubble decreases. In Figure 8 (d) presenting C_p close to the wing-tip, the separation and reattachment are not observed and the integration of the pressure coefficient on a wing-tip side is greatly decreased by the wing-tip effect. The integration of the pressure coefficient is lower than that of the two-dimensional airfoil flow in all locations. It is noted in detail that the suction peak is suppressed and the positive pressure slightly decreases on the lower surface. Figure 9 shows the distribution of sectional lift coefficients (c_l) as the function of normalized span position. Sectional lift coefficients are the integration of the pressure coefficient. It is clarified that the effect of the wing-tip is larger than that of the wing-body interference.

The result of the two-dimensional airfoil flow shows that the lift curve is nonlinear. When the flow regime changes from the attached flow to the separated flow, the lift coefficient is enhanced by the laminar separation bubble. It was reported that this transition of the flow regime makes the lift curve nonlinear. Although the same transition is observed

as shown in Fig. 7, the lift curve is linear in a complete aircraft configuration. It is considered that the reason why the lift curve becomes linear is due to the three-dimensional effects. This might be because the flow change by generation of laminar separation becomes milder due to the wing-tip effects.

5. Conclusions

The aerodynamic performance of the Mars airplane with a complete aircraft configuration is analyzed by performing RANS simulations. The results clarify the outline of the flow field, how the main wing, the body, the tail wing and others affect to the aerodynamic performance.

The decomposition analysis shows the most dominant factor to determine the aerodynamic performance is the main wing. The main wing has a more than 90% contribution to the lift coefficient, and a more than 60% contribution to the drag coefficient. To improve the aerodynamic performance of the main wing is especially effective toward the optimum design of the Mars airplane. The other components contribute approximately 10 % to the lift coefficient and 10 to 40 % to the drag coefficient. Changing the shape of these components for reduction of drag raises the whole aerodynamic performance.

Three-dimensional effects such as the wing-body interference and the wing-tip effect affect the flow regime on the upper surface. These three-dimensional effects seem to be the reason why the lift curve becomes linear.

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Fig. 8. Pressure coefficient distributions at $\alpha = 6$ deg.

Fig. 9. Sectional lift coefficient in the span-direction.