Aerodynamic performance of control surfaces on Mars airplane balloon experiment two

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Abstract
We redesigned the Mars Airplane Balloon Experiment Two (MABE-2) based on MABE-1 to improve the vehicle’s stability and controllability. Following the redesign, the MABE-2 vehicle had a larger horizontal tail volume than that of MABE-1 for improved stability performance. In addition, to further improve the stability and control characteristics, a rectangular planform was employed for the horizontal tail wing; in contrast, MABE-1 had a tapered planform. The vertical tail position of MABE-2 was moved to the end of the horizontal tail wing, because the vertical tail of MABE-1, which was positioned at the mid span of the horizontal tail wing, showed aerodynamic interaction with the horizontal tail wing. In this paper, we discussed the aerodynamic performance of a control surface based on computational fluid dynamics with variation in the deflection angle between the control surface and the horizontal tail (elevator), and we examined the effects of this redesign on longitudinal control characteristics. Numerical investigations confirmed the linear variation in the pitching moment and the aerodynamic force with the changing elevator deflection angle in MABE-2. Surface pressure observations indicated that MABE-2 shows a smooth variation in the pressure distribution with changing elevator deflection angle, while MABE-1 does not. These results demonstrate that the aerodynamic control characteristics of MABE-2 were improved in comparison to those of MABE-1.

Keywords : Mars airplane balloon experiment, Computational fluid dynamics, Horizontal tail wing, Aerodynamic control, Longitudinal motion

1. Introduction

Mars exploration using an airplane flying in the Martian atmosphere is expected to be a candidate solution for conducting wide-range exploration. At the Langley Research Institute at NASA, Aerial Regional-Scale Environmental Survey (ARES) Mars Scout airplane (Braun et al., 2006) efforts demonstrated a compelling scientific rationale and a mature mission and flight system concept; however, this approach has not been put into practical use so far. In Japan, this approach has been studied by the Mars exploration aircraft research group, consisting of researchers at JAXA and universities, with the aim of realizing exploration using a winged aircraft (Fujita et al., 2016a; Fujita et al., 2016b), as shown in Fig. 1. A considerable problem in designing such an aircraft is the low-density atmosphere of Mars. To acquire further aerodynamics knowledge, computational fluid dynamics (CFD) simulations and experiments in low-pressure wind tunnels have been applied.

Although these approaches can be applied to obtain fundamental aerodynamics data, control and aerodynamics-structure coupled characteristics should be studied using a detailed model. To examine these issues, flight testing at high altitudes on Earth is a promising solution because the air density at an altitude of approximately 40 km on Earth is almost equivalent to that of Mars. The Mars exploration aircraft research group conducted the first high-altitude flight test (Mars
Airplane Balloon Experiment One: MABE-1) using JAXA’s scientific balloon on June 12, 2016 (Oyama et al., 2017). The experimental model, as shown in Fig. 2, was designed to be stored in an entry capsule with an inner diameter of approximately 1 m by folding the wing and the aft fuselage. It was planned to fly over a range of approximately 100 km. MABE-1 had a main wing whose chord and span lengths were 0.49 m and 2.4 m, respectively, and whose fuselage length and height were 2.3 m and 0.4 m, respectively. With a scientific balloon launched by JAXA, the model rose to an altitude of approximately 36,000 m, which closely resembled the low-altitude atmosphere of Mars. Although several data could not be acquired, partial aerodynamics data for the experimental aircraft were successfully obtained.

However, there were several problems regarding the longitudinal stability of the aircraft; these arose particularly because of the aerodynamic characteristics, which were determined by the planform geometry, area, and volume of the tail wing. In addition, MABE-1 required additional ballast, which increased the gross weight at the nose, to attain center-of-gravity (CG) balance (30%c).

In our previous study (Tomisawa et al., 2017) proposing the next design of the experimental airplane, MABE-2, we redesigned the tail wing in view of the longitudinal stability and CG correction according to the flight-testing results of MABE-1. One of the major improvements was the use of a rectangular horizontal tail wing in contrast to the inverted delta-shaped wing used in MABE-1. An airfoil that is thinner that of MABE-1 was employed in MABE-2. The rectangular planform could maintain a constant chord length in the span direction, minimizing variance in the local Reynolds number. According to the results obtained using CFD, the aerodynamic stability was thereby improved.

This design also aims to suppress flow separation and improve the effectiveness of the elevator. Thus, in this study, the aerodynamic characteristics of a control surface are acquired by CFD. The results are compared to numerical aerodynamics results of MABE-1 and the rudder effect and the influence of wake interference are investigated with variation in the elevator angle.

2. Overview of MABE-2 design

Both MABE-1 and MABE-2 were conceptually designed under the constraint that the aircraft can be stored in a cylindrical entry capsule with a radius of 0.4996 m, assuming folding mechanics (Oyama et al., 2017; Tomisawa et al., 2017). In Fig. 3, the planform geometries of the horizontal tail wings of MABE-1 and MABE-2 are compared. MABE-1 employed a tapered planform; however, because the tapered wing’s local Reynolds number changed in the spanwise direction due to nonuniform chord length along the span direction, which causes a low local Reynolds number at the tip of the horizontal tail wing, we decided that this should be modified. Thus, MABE-2 choose a rectangle planform among several candidate such as an oval, a triangle, and a taped planform for the horizontal tail wing and the elevator to maintain a uniform chord length distribution. In MABE-2, a rectangular horizontal tail (chord length = 350.0 mm, aspect ratio = 2.0, and horizontal tail volume = 0.5) is employed after conducting the parametric study by changing the aspect ratio of horizontal tail wing’s planform under the constraint of being able to be stored in an entry capsule. Assuming that the area of the planform is constant, a planform with a lower aspect ratio can be easily affected by the wake from the main wing and the fuselage; however, a planform with a higher aspect ratio exhibits a lower local Reynolds number in addition to structural weakness. Taking account of these issues, appropriate values for the chord length and the aspect ratio of the horizontal tail wing were selected. Once the horizontal tail planform was selected, the elevator, a control surface, was determined to have a volume equivalent to that of MABE-1. The vertical tail wing of MABE-2 was also determined to
have a volume equivalent to that of MABE-1. Its chord length was set by subtracting the chord length of the elevator from that of the horizontal tail wing. It was located at the end of the horizontal tail wing in MABE-2 compared to its position at the mid span in MABE-1. The objective here was to avoid geometrical and aerodynamic interactions acting on the elevator. The length of the boom connecting the fuselage and the horizontal wing was determined by the horizontal tail volume after the horizontal tail planform was designed. In addition, the structural weight calculated based on the structural strength of the main wing, the boom, and tail wings, assuming the material was carbon fiber-reinforced plastic that strengthens under dynamic pressure, was 159.4 Pa (at Mach 0.6), and the safety ratio was 3 (Tomisawa et al., 2017).

![Diagram](image_url)

**Fig. 3** Comparison of three views of the airplane for the balloon experiment. (a)MABE-1 and (b)MABE-2.

### 3. Numerical method for aerodynamic evaluation

In this study, CFD simulations are applied to MABE-1 and MABE-2 models as shown in Fig. 3 to investigate their aerodynamic control capability when the elevator deflection angle is changed. Computational conditions include a Mach number of 0.2, a Reynolds number of $1.7 \times 10^4$, a reference length of 0.49 m, which is a chord length of the main wing; the dynamic pressure is 1.4 Pa. The governing equation is the Navier–Stokes equation, and a Reynolds-averaged Navier–Stokes simulation (RANS) is conducted using Menter’s Shear Stress Transport (SST)-2003 (Menter 1994; Menter et al., 2003) as a turbulent model that includes Menter $Re_{	ext{t}}$, which is a laminar-transition prediction model. For the computation, the Fast Aerodynamic Routine, FaSTAR (Hashimoto et al., 2009; Hashimoto, et al., 2012), is applied. Figure 5 shows the computational mesh. The unstructured mesh was generated by using the height of the first mesh cell (the minimum spacing) off the wall required to achieve $y^+=1$ using flat-plate boundary layer theory.
4. Validation of numerical method

4.1. Grid dependency study

Three different grid resolutions with a changing number of grid \( N \)—coarse (\( N = \text{approx.} \ 5.2 \text{ million nodes})\), medium (\( N = \text{approx.} \ 8.0 \text{ million nodes})\) and fine (\( N = \text{approx.} \ 12.4 \text{ million nodes})\)—are calculated for investigating grid dependencies. Pitching moment coefficients \( C_M \) (see the definition in subsection 5.1) results are compared by means of a generalized Richardson extrapolation (GRE) (Brezinski et al., 1991.). Figure 5 shows the results of \( C_M - (1/N)^3 \), angle of attack \( \alpha = 0.0 \). The GRE result appears to drop somewhere around fine and medium grid resolutions, while the coarse grid resolution did not show a near value with the GRE result. Thus, we decided to use the medium grid resolution to acquire the numerical result for this paper.

4.2. Comparison with experimental data

Before the numerical investigation, we compared the numerical result using the decided grid resolution in the previous subsection and the wind tunnel testing using the planetary environmental wind tunnel. (Anyoji et al., 2013) Reynolds number was \( 3.3 \times 10^4 \) in both the numerical result and the experimental result when the MABE-1 is used as a model. Figure 6 shows the comparisons of the lift coefficient \( C_L \) with changing angles of attack (\( \alpha \)). According to this result, the difference between the numerical result is almost 3% higher than the experimental result throughout \( \alpha \). The lift slope \( \partial C_L / \partial \alpha \) from \( \alpha = 0^\circ \) to \( \alpha = 6^\circ \) is 0.0793 by the numerical result, and 0.0770 by the experiment. These results suggest that the numerical result agree well with the experimental result.

Fig. 4 Computational grid.

Fig. 5 Results of grid dependency study.

Fig. 6 Comparison of \( C_L \) between CFD and the wind tunnel testing.
5. Results and discussion

In this study, CFD results for MABE-1 and MABE-2 are compared in terms of the control surface characteristics of the horizontal tail (elevator) by observing the control forces and flowfield. The deflection angles of the elevator $\delta e$ are validated at $0$, $-5$, and $-10^\circ$, as shown in Fig. 7. For the aerodynamic evaluations, the Reynolds number was set to $3.3 \times 10^5$ (with the wing chord length used as the reference length) and the Mach number was set to 0.2. We investigated the aerodynamic forces and flowfield after verifying the convergence of the drag and lift forces for every case.

5.1. Controllability by deflecting control surfaces

$C_M$ around MABE-1 and MABE-2 (whole configurations of aircraft) are shown in Fig. 8. $C_M$ was calculated around 30%chord length of the main wing. The change of $C_{M5}$ with different $\alpha$ shows the controllability at a given $\alpha$. According to Fig. 8, the variation of $C_M$ of MABE-2 becomes linear comparing to that of MABE-1 for every $\delta e$. It suggests that the controllability of MABE-2 was improved in the pitching motion and it makes the design of the control sequence easier because of the smooth response of the control surfaces. In MABE-1, the difference of $C_M$ between two $\alpha$ values, $\Delta C_M$, in $\delta e = -5$ and $0^\circ$ are smaller than those of $\delta e = -10^\circ$. This means that the controllability at low $\alpha$ is worse than at high $\alpha$ and the control should be non-linear. On the other hand, $\Delta C_M$ is approximately equivalent to $\alpha$. It was also confirmed that the variation of $C_M$ along with that of $\alpha$ are linear while there was inflection point at $\alpha = 0.0$ for all three $\delta e$. This suggested that controllability was improved in MABE-2. Moreover, $\partial C_M/\partial \delta e$ at low $\alpha$ for MABE-2 was larger than that for MABE-1. According to this result, the longitudinal controllability at low angles of attack was improved through the redesign. Comparing the increment $\alpha$ when $C_M$ is 0, that is trimmed $\alpha$, is approximately $0^\circ$ from $\delta e = 0$ to $-5^\circ$ and approximately $7^\circ$ from $\delta e = -5$ to $-10^\circ$. These results imply elevator control did not impact the pitching moment at low $\delta e$ while the large impact at higher $\delta e$ was observed. On the other hand, the increment $\alpha$ at trimmed $\alpha$ was approximately $2^\circ$ in MABE-2 at each $\delta e$ variation. This result suggests that the impact to the pitching moment at low $\delta e$ was improved. However, additional $2^\circ$ increment of trimmed $\alpha$ is required (Anyoji et al., 2013) for sufficient control, and we will study it as our future work.

5.2. Aerodynamic forces on control surfaces

Figure 9 compares the linear response of the control surfaces. Figure 10 compares the pressure coefficient distributions at the mid-span of the horizontal tails between MABE-1 and MABE-2. According to Fig. 9, $C_L$ of the horizontal tail wing showed a linear response in MABE-2 while that in MABE-1 showed a non-linear response for every $\delta e$. Thus, the $C_M$ of the MABE-2 also showed a linear response, as discussed in the previous subsection. In addition, in MABE-1, the variation in $C_L$ is small; that is, the sensitivity of $\delta e$ to the aerodynamic force is not high. In contrast, the constant increment of $C_L$ owing to $\delta e$ was confirmed.

Figure 10(a) indicates that the difference of $C_P$ between $\delta e = -5^\circ$ and $\delta e = 0^\circ$ is smaller than the difference between $\delta e = -5^\circ$ and $\delta e = -10^\circ$. From this result, the aerodynamic force of the horizontal tail of MABE-1 became non-linear, as shown in Fig. 9(a). Contrastingly, from Fig. 10(b), $C_P$ distributions both on the upper and the lower surfaces constantly changed with changing $\delta e$. Thus, the aerodynamic force on the horizontal tail of MABE-2 showed linear variation, as shown in Fig. 9.

5.3. Surface pressure distributions

Figure 11 shows a comparison of the surface $C_P$ distributions between MABE-1 and MABE-2 with changing $\delta e$ at $\alpha = 0^\circ$. The increment of pressure from the leading edge of the horizontal tail wing to the aft of horizontal tail wing and the elevator on the upper surface of MABE-1 was relatively small at $\delta e = -5^\circ$; however, that of $\delta e = -10^\circ$ rapidly increased only at the root of the horizontal tail wing. In contrast, the positive pressure on the upper surface of MABE-2 was slightly increased from $\delta e = 0^\circ$ to $\delta e = -10^\circ$ on almost the entire upper surface. Because the span length of the elevator of MABE-2 was longer than that of MABE-1, the elevator could deflect the flow on the horizontal tail wing to control the pitch direction of the aircraft better than that of MABE-1 and the influence of the elevator was enhanced. In addition, the vertical tails were located at the wing tip of the horizontal tail wing in MABE-2, while they were located at the mid-span of the horizontal tail wing in MABE-1. Thus, the flow field on the horizontal tail wing was almost uniform; by avoiding aerodynamic interaction with the vertical tail wing in MABE-2, aerodynamic control becomes easier in MABE-2 than in MABE-1. This leads to linear aerodynamic variations, as discussed in the previous subsection, because the camber effect of the elevator was enhanced.
Fig. 7 Computational geometries and grid resolutions around the horizontal tail. (a) Cross sections of the horizontal tail wing and variations in $\delta e$, (b) grid around the horizontal tail wing of MABE-1 ($\delta e = 0^\circ$, $\delta e = -5^\circ$, and $\delta e = -10^\circ$) and (c) grid around the horizontal tail wing of MABE-2 ($\delta e = 0^\circ$, $\delta e = -5^\circ$, and $\delta e = -10^\circ$).

Fig. 8 Comparisons of $C_M$ variation with changing $\delta e$ around the complete configuration of aircraft. (a) MABE-1 and (b) MABE-2.
Fig. 9  Comparison of $C_L$ variation with changing $\delta e$ around the horizontal tail wing with changing $\delta e$. (a) MABE-1 and (b) MABE-2.

Fig. 10  Comparison of $C_P$ distributions at mid-span for the horizontal tails.

Fig. 11  Comparison of $C_P$ distributions on the horizontal tails. (a) MABE-1 and (b) MABE-2.
6. Conclusions

A numerical investigation of the aerodynamic performance of MABE-2’s horizontal tail wing control surface was conducted and compared with that of MABE-1. The flowfield was evaluated using an unstructured-mesh-based flow solver. The elevator deflection angle was changed to 0, -5, and -10°.

Numerical results for the pitching moment coefficient and the lift coefficient of the horizontal tail wing with various elevator deflection angles suggests that the control characteristics of the horizontal tail could be improved. By observing the surface pressure distribution on the horizontal tail wing, a smoother variation in the positive pressure distribution was confirmed in MABE-2 compared with MABE-1 owing to the use of a rectangular planform. In addition, the installation of vertical tails at the end of the horizontal tail in MABE-2’s design was effective in improving the control surface because the vertical tails of MABE-1 showed significant aerodynamic interaction that reduced the aerodynamic performance of the horizontal tail wing.

In the future, we will investigate detailed flow information in the MABE-2 using higher accuracy numerical methods such as a large eddy simulation and wind tunnel testing.

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