Variable-Pressure Wind Tunnel Test of Airfoils at Low Reynolds Numbers Designed for Mars Exploration Aircraft

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Recently, aerial Mars exploration systems have been actively researched. Because the atmospheric density of Mars is almost one-hundredth to that of Earth’s, the flight Reynolds number becomes low (Re = 10^4 ~ 10^5). In low Reynolds numbers, the flow around a wing tends to separate and conventional airfoils cannot satisfy the given performance requirements for Mars exploration aircraft. In recent years, Sasaki et al. researched new airfoils that have high lift-to-drag ratio at low Reynolds number using evolutionary multi-objective optimization and computational fluid dynamics. In this research, two-dimensional wind tunnel test of three airfoils proposed by Sasaki et al. is conducted to investigate their actual aerodynamic characteristics at Reynolds number 2.0 × 10^4. The Ishii airfoil with good performance at low Reynolds number is used as the benchmark. The result of the wind tunnel test showed that the lift curve of the three airfoils is linear, and their maximum lift coefficient and stall angle are larger than those of Ishii. Particularly, the three airfoils’ lift-to-drag ratio is superior to the Ishii airfoil by more than 30%.

Key Words: Low Reynolds, Wind Tunnel, Airfoil, Mars Aircraft

Nomenclature

\[ Re \] : Reynolds number
\[ L \] : lift
\[ D \] : drag
\[ Cl \] : lift coefficient
\[ Cd \] : drag coefficient
\[ c \] : chord length
\[ y \] : coordinate normal to the chordwise

1. Introduction

Currently, JAXA/ISAS has developed a Mars exploration mission via aircraft called MELOS, which is expected to be launched in early 2020’s. Aerial exploration is used as opposed to conventional planetary rover because aerial exploration enables wide area observation.

Mars’ atmospheric density is about 1/100 of Earth’s density (Table. 1), and the aircraft must cruise at low speeds for exploration. Therefore, inflight Reynolds numbers become very small (from 10^4 to 10^5) and the aerodynamic characteristics change compared to flights in Earth’s atmosphere. A high performance airfoil for low Reynolds numbers is needed for the design of Mars exploration aircraft1).

In low Reynolds number flight, even a small difference in the airfoil section (especially the shapes of leading and trailing edges) affects the aerodynamic performance significantly and aerodynamic characteristics at low Reynolds numbers have been found to have strong nonlinearity2,3,4). Separation bubbles are one of the factors that affect the aerodynamic performance. According to reference 2), at low Reynolds numbers, the separated flow over a wing reattaches while transitioning to turbulent flow, creating a circular flow known as a laminar separation bubble as shown in Fig. 1. These laminar separation bubbles are classified into two types, “Short bubbles” and “Long bubbles”. A short bubble is a separation bubble that moves forward to the leading edge by shortening its length as the angle of attack gets larger. A long bubble is a separation bubble that extends its length with moving its reattachment position backward to the trailing edge. Much research has verified that reverse-flow areas exist and that pressure coefficient distribution is flat when separation bubbles occur as shown in Fig. 2, which is referred to reference 2). The behavior of this separation bubble gives a non-linearity to the lift characteristic of the wing and influences the stall angle. In this way, separation bubbles greatly impact aerodynamic performance. Therefore, it is very important to observe the phenomenon of separation bubbles and consider them.

Table 1. Comparison of environment between Mars and the Earth.

<table>
<thead>
<tr>
<th></th>
<th>Mars</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration of gravity [m/s^2]</td>
<td>3.66</td>
<td>9.81</td>
</tr>
<tr>
<td>Atmospheric pressure [kPa]</td>
<td>0.6-1</td>
<td>101.3</td>
</tr>
<tr>
<td>Atmospheric density [kg/m^3]</td>
<td>0.0167</td>
<td>1.225</td>
</tr>
<tr>
<td>Coefficient of viscosity [kg/(ms)]</td>
<td>1.289×10^{-4}</td>
<td>1.789×10^{-3}</td>
</tr>
<tr>
<td>Gas constant [J/(kgK)]</td>
<td>192</td>
<td>287</td>
</tr>
<tr>
<td>Ratio of specific heat [-]</td>
<td>1.29</td>
<td>1.4</td>
</tr>
<tr>
<td>Speed of sound [m/s]</td>
<td>228</td>
<td>340</td>
</tr>
</tbody>
</table>
Based on the research of multi-objective airfoil shape optimization, each drag coefficient of the airfoils proposed by CFD becomes larger than that of the Ishii airfoil when their lift coefficient exceeds one. Ohyama et al. have mentioned that Mars exploration aircraft are not capable of carrying a high performance propeller, so the drag coefficient of the wing should be reduced as much as possible. Therefore, requirement ② was established.

The Ishii and optimized airfoils are shown in Fig. 3. Figure 4 shows a wind tunnel test model of No. 1. All wings have the chord length of 125 mm and a span of 500 mm.

2. Experimental Setup
2.1. Test airfoils
A 20% increase of maximum lift-to-drag ratio compared to the Ishii airfoil is required for the optimized airfoils. The Ishii airfoil was developed by the famous hand-launched glider world champion Mr. Ishii himself for his own competition plane based on his many years of experience. It has fairly good aerodynamic performance at low Reynolds number. For example, the maximum lift-to-drag ratio of the Ishii airfoil at a Mars Reynolds number is 12.9, which is larger than currently existing airfoils. However, the performance of Ishii airfoil is not satisfactory for Mars exploration aircraft. Therefore, Sasaki et al. have tried to find optimal airfoils using GA associated with CFD. As a result, they acquired many types of airfoils that have 20% better lift-to-drag ratio compared to the Ishii airfoil. Three airfoils out of the optimized airfoils were selected based on the following conditions.
① Feasibility of manufacturing a wind tunnel test model
② Lift coefficient less than one
③ More than a 20% increase of the maximum lift-to-drag ratio of Ishii airfoil (12.9)

Sasaki et al. have studied multi-objective airfoil shape optimization using Genetic Algorithm (GA) associated with Computational Fluid Dynamics (CFD). Their research found possible types of airfoils numerically, but require further investigation using wind tunnel testing.

The purpose of this study is to evaluate and discuss these optimized airfoils.
3. Test Results and Consideration

Wind tunnel tests were conducted to measure lift, drag and pitching moment coefficients. The test Reynolds number was $2.0 \times 10^4$. The angles of attack were changed from $-10$ to 20 [deg.] in 1 [deg.] increments.

Figure 8 shows the lift coefficients. The lift curve slopes are almost linear and show almost the same lift coefficient values from $-10^\circ$ to $5^\circ$, but the lift coefficient of No.3 is consistently high from $-3^\circ$ to $6^\circ$. The upper surface of No.3 has a hollow shape, which accelerates the formation of the separation bubble. The authors believe that the shape triggers the separation bubble on No.3 from a lower angle of attack. Each maximum lift coefficient is increased by 29% in No.1, 22% in No.2, and 17% in No.3. Furthermore, stall angles of all optimized airfoils are superior to that of Ishii airfoil.

Figure 9 shows the drag coefficients. Ishii airfoil and No.1 have similar drag curves, while No.1 and No.2 showed large reduction of drag at an angle of attack of $8^\circ$. The rates of decrease are 41% in No.1, and 28% in No.2.

Figure 10 shows the lift-to-drag ratios of all airfoils. The maximum lift-to-drag ratio of all optimized airfoils are better than that of Ishii airfoil, improving 38% in No.1, 34% in No.2, and 35% in No.3 compared to Ishii airfoil.
pictures taken by using PIV (Particle Image Velocimetry) method\(^6\). In the range of the angle of attacks, differences of their flowfields are relatively clear.

In Figs. 11 – 22, the vertical line denotes the ratio of the position from the upper wing surface to the chord and the horizontal line represents flow velocity. The color bars in each picture show the local velocity to the uniform velocity. As shown in the graph of Fig. 11, the flow is mostly static at the separation point. Moreover, there is a reverse-flow called separation bubbles. The reverse flow is shown with red dots. At the reattachment point, the velocity increases and the reverse-flow disappears.

The flowfields at an angle of attack of 6° are shown from Fig. 11 to Fig. 14, 8° from Fig. 15 to Fig. 18, and 10° from Fig. 19 to Fig. 22.

First, flowfields at an angle of attack of 6° are discussed. As shown in Fig. 8, increment of the lift coefficient of Ishii airfoil and No.3 becomes small from 5°, while the lift coefficient of No.1 and No.2 still become larger. According to the flowfields, Ishii airfoil and No.3 have similar velocity distribution and positions of separation and reattachment, while No.1 has a slight separation around the leading edge although No.1 and No.2 have similar velocity distribution. The authors concluded that growth of separation bubbles of Ishii airfoil and No.3 (Fig. 11 and 14) causes the drop of increment of the lift coefficient and attached flow of No.1 and No.2 (Fig. 12 and 13) promotes continuous increase of the lift coefficient.

Second, at an angle of attack of 8°, the drag coefficients of Ishii airfoil and No.3 are much larger than that of No.1 and No.2. The authors consider that it is related to very large separation bubbles of Ishii airfoil and No.3. Besides, Ishii airfoil and No.3 transition to stall as is clear from Fig. 8. It is also expected from the flowfields. According to the upper figures that show velocity distribution of Fig. 15 and 18, it is clear that the velocity is not recovered enough on the upper surface at trailing edge, which means the flow does not attach completely.

Third, at an angle of attack of 10°, only the Ishii airfoil experiences a stall. No.1 has a separation around the leading edge but the flow reattaches immediately and the velocity recovers enough. On the other hand, No.2 has a late reattachment and the amount of velocity recovery is less than that of No.1, which is known by comparing their velocity distribution around their trailing edges. No.3 also has the reattched flow but the amount of velocity recovery is much less than that of No.1 and No.2. That is why No.3 is expected to reach a stall soon. It is seen, airfoils No.1 and No.2 have a smaller separation area compared to Ishii and No.3 airfoils. The authors concluded that the difference of their upper surface shapes results in the condition. The shapes of upper surfaces of No.1 and No.2 are closer to an arc than that of the Ishii airfoil and No.3, which allows them to maintain attached flow at a higher angle of attack than the Ishii airfoil and No.3.

Fig. 11. Ishii (angle of attack at 6°).

Fig. 12. No.1 (angle of attack at 6°).

Fig. 13. No.2 (angle of attack at 6°).

Fig. 14. No.3 (angle of attack at 6°).
Fig. 14. No.3 (angle of attack at 6°).

Fig. 15. Ishii (angle of attack at 8°).

Fig. 16. No.1 (angle of attack at 8°).

Fig. 17. No.2 (angle of attack at 8°).

Fig. 18. No.3 (angle of attack at 8°).

Fig. 19. Ishii (angle of attack at 10°).
4. Conclusion

A hollow triangle shape on the upper wing surface causes separation bubbles at low angle of attack, increasing the lift coefficient, however the drag coefficient also increases. On the other hand, an arc shape on the upper wing surface can reduce separation bubbles and also increases the angle of stall. In conclusion, the latter characteristic and high lift-to-drag ratio are suitable for an aircraft. That is why No.1 is the most advantageous among all airfoils tested in this study.

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References