Analysis of Owl-like Airfoil Aerodynamics at Low Reynolds Number Flow

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Aerodynamic characteristics and flow fields around an owl-like airfoil at a chord Reynolds number of 23,000 are investigated using two-dimensional laminar flow computations. Computed results demonstrate that the deeply concaved lower surface of the owl-like airfoil contributes to lift augmenting, and both a round leading edge and a flat upper surface lead to lift enhancement and drag reduction due to the suction peak and the presence of the thin laminar separation bubble near the leading edge. Subsequently, the owl-like airfoil has higher lift-to-drag ratio than the high lift-to-drag Ishii airfoil at low Reynolds number. However, when the minimum drag is presented, the Ishii airfoil gains lift coefficient of zero while lift coefficient of the owl-like airfoil does not becomes zero. Furthermore, a feature of unsteady flow structures around the owl-like airfoil at the maximum lift-to-drag ratio condition is highlighted.

Key Words: Low Reynolds Number, CFD, Aerodynamic Characteristics, Mars Airplane

Nomenclature

- $a_c$ : Sound speed
- $c$ : Chord length
- $C_L$ : Lift coefficient
- $C_D$ : Drag coefficient
- $C_{p}$ : Surface pressure coefficient
- $dt^*$ : Computational time step
- $L/D$ : Lift-to-drag ratio
- $N$ : Number of grid points
- $R$ : Reattachment location
- $Re$ : chord-based Reynolds number
- $S$ : Separation location
- $t^*$ : Non-dimensional time
- $u$ : Chord direction velocity
- $x, y$ : Cartesian coordinate
- $y_L$ : Lift direction coordinate
- $\alpha$ : Angle of attack
- $\xi, \eta$ : Computational coordinate
- $\omega_z^*$ : Non-dimensional spanwise vorticity

Subscripts

- $\infty$ : Freestream

1. Introduction

The exploration of Mars is a hot topic of researches across the globe. Several types of exploration systems are currently considered, e.g. a rover, a satellite, an aircraft type, and so forth. Each exploration system has different role in particular missions. For example, the rover explores the geological features, the satellite captures the geographical features, and the airplane investigates the atmospheric and environmental features (but not limited). These systems are required to improve own capacity and ability to achieve missions with low risks.

A main focus of this study is the aircraft-type Mars explore named Mars airplane. When the Mars airplane flies on Mars, it would encounter two major problems. One problem is that it is difficult to gain a sufficient lift force because the atmospheric density of Mars is 100 times less than that of Earth. All air vehicles that will fly on Mars will face this problem. The other arises from the mission conditions. The size of the airplane is limited due to the space constraint of the transport capsule from Earth to Mars. Moreover, low speed flight is required to carry out environmental exploration. From these factors, it is expected that Mars airplanes will fly in the regime of the low Reynolds numbers between $10^3$ and $10^5$. Thus, understanding of fundamental aerodynamic characteristics associated with an airfoil under the low Reynolds number conditions becomes an important part in the design of Mars airplane.

Fig. 1 shows that a decrease in the Reynolds number degrades the aerodynamic performance of smooth airfoils. The smooth airfoil is generally utilized under high Reynolds number conditions. It is clearly observed that the maximum lift-to-drag ratio of a smooth airfoil decreases with the decreasing Reynolds number. The reason is that the flow around the airfoil is initially laminar and is prone to laminar separation in the low Reynolds number condition. After laminar boundary layer separation, laminar-to-turbulent transition and reattachment occurs, that is called the laminar separation bubble. The behavior of such laminar separation bubble has been investigated by various researchers; the laminar separation bubble affects stalling behavior and leads to nonlinearity in $C_L-\alpha$ curve.}

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Schmitz\textsuperscript{2,5}) has suggested that airfoils with the following geometric features show good aerodynamic performance under low Reynolds number conditions\textit{(O}(10^4-10^5)\textit{)}:

1) Sharp geometry at the leading edge.
2) A flat upper surface.
3) A deep camber.

Anyoji et al.\textsuperscript{6}) have investigated the aerodynamic performance of an airfoil named Ishii airfoil which has the above features 2) and 3) by computations and experiments. As a result, the Ishii airfoil presents high aerodynamic performance compared with conventional airfoils such as NACA0012 and NACA0002\textsuperscript{7}). Furthermore, Aono et al.\textsuperscript{8}) have showed that lower surface geometry of the Ishii airfoil contributes to lift enhancement by comparing two types of thin, asymmetric and similar geometric airfoils; SD7003 and the Ishii airfoil. Therefore, the Ishii airfoil is a clear candidate for the main wing of Mars airplane. However, in order to increase capacity of payload and reduce the road on the propulsion system, further improvement of lift-to-drag ratio of the main wing is required.

From the background mentioned above, we are interested in the avian wings. The present work focuses on the owl wing because the wing inherits several features as mentioned above. Furthermore, owl approaches its prey at a moderate speed of 2.5 m/s to 7.0 m/s\textsuperscript{9}), and flight Reynolds numbers becomes 25,000 to 70,000 based on a mean chord length of approximately 150 mm. These Reynolds number regimes overlap the Mars airplane flight condition. Liu et al.\textsuperscript{10}) experimentally have measured the owl wing shape and provided mathematical formulation of its shape. However, aerodynamic performance of the owl wing have not been analyzed and understood yet.

The objective of this paper is to understand basic aerodynamic characteristics of the owl-like airfoil under the low Reynolds number conditions and to gain the knowledge for design of the low Reynolds number wing. Flow around the owl-like airfoil is simulated using two-dimensional laminar computations (2D-Laminar). From computational results, aerodynamic force coefficients, time-averaged flow-fields, surface pressure coefficients, and unsteady flow structure of the owl-like airfoil are discussed.

2. Materials and Methodologies

2.1. Model wing and computational condition

The present study considers two airfoils; one is an owl-like and another is the Ishii airfoil (shown as Figs. 2). The owl-like airfoil is the cross-section of owl wing at 40% of span length. This airfoil geometry is constructed based on the experimental data\textsuperscript{10}). The owl-like airfoil has a maximum thickness and camber of 5.4% at \(x/c=0.11\) and 4.9% at \(x/c=0.47\), respectively. On the other hand, the Ishii airfoil is designed for gliding by Mr. Ishii who was a champion of a free flight contest of hand launch glider. This airfoil has a maximum thickness and camber of 7.1% at \(x/c=0.25\) and 2.3% at \(x/c=0.62\), respectively. More detailed purpose of design of the Ishii airfoil can be found in Koike and Ishii\textsuperscript{11}).

The freestream Mach number is set to 0.2 at which compressibility can be ignored. Chord- and freestream-based Reynolds number \((Re_c)\) is set to 23,000. The angles of attack are selected ranging from -3.0° to 9.0°.

2.2. Computational methods

The computational code LANS3D\textsuperscript{12}) (developed in ISAS/JAXA) is adopted and two-dimensional laminar computations are conducted. The two-dimensional compressible Navier-Stokes equations normalized by chord length \((c)\) and sound speed \((a_s)\) at freestream and generalized curvilinear coordinates are employed as the governing equations. The spatial derivative of the convection are evaluated by SHUS\textsuperscript{13}) + third-order MUSCL\textsuperscript{14}) schemes, and that of the viscous term is evaluated by second-order central differencing. For time-integration, the second-order backward difference of alternating directional implicit symmetric Gauss-Seidel implicit method\textsuperscript{15}) with five times sub-iterations\textsuperscript{16}) in each time step is adopted. The computational time is \(dt=2.5\times10^{-4}\) \(a_s/c\) in non-dimensional time, corresponds to the maximum Courant-Friedrichs-Lewy (CFL) number becomes approximately 1.5.

2.3. Computational mesh and boundary conditions

Computational meshes around the owl-like airfoil and the Ishii airfoil are shown in Figs. 3. The C-type structure mesh is utilized for the computational mesh. Number of grid points of are 615 points for traverses clockwise (\(\zeta\)) around the airfoil and 101 points for normal to the surface \((\eta)\), so that total

Fig. 1. The diagram of Reynolds number effect on maximum lift-to-drag ratio associated with smooth airfoils\textsuperscript{5}.

Fig. 2. Airfoil profiles.
points are 62,115 points. The first grid points away from the airfoil surface are fixed for all grids and set to be \(0.03c/\sqrt{Re} \approx 1.98 \times 10^{-4}\). The distance from the airfoil surface to the outer boundary is \(30c\). At the outflow boundary, all variables are extrapolated from one point inside of the outflow boundary. On the airfoil surface, no-slip and adiabatic-wall conditions are adopted.

It should be mentioned that the number of grid points and grid distribution used in current study are determined by grid sensitive analysis. Moreover, grid generation tools and LANS3D have been tested and validated through in a series of previous studies with regard to low Reynolds number flow simulations. \(^{6,7,8}\)

(a) The owl-like airfoil  
(b) The Ishii airfoil

3. Results and Discussion

3.1. Aerodynamic coefficients

Aerodynamic force coefficients of the owl-like airfoil are discussed. Lift and drag coefficients, and lift-to-drag as a function of the angle of attack are plotted with those of the Ishii airfoil as a reference in Figs. 4, 5 and 6. Circles and diamonds indicate results associated with the owl-like and the Ishii airfoil, respectively. Note that the angle of attack used in this study is not increment from the zero-lift angle of attack but the geometric angle of attack with respect to the freestream.

The owl-like airfoil gains higher lift coefficient than the Ishii airfoil at all angles of attack. Strong nonlinearity can be seen in a lift curve of the owl-like airfoil at the angles of attack between 3.0° and 4.5°.

A drag coefficient of the owl-like airfoil shows unique characteristics while that of the Ishii airfoil has similar behavior to conventional airfoils (e.g. NACA0012). It should be noted that the drag coefficients at the angle of attack of 4.5° and 6.0° are almost the same whereas lift coefficient increases with increasing the angle of attack. Furthermore, the Ishii airfoil presents the lowest drag coefficient at the angle of attack of approximately -1.0° at which the lift coefficient is zero. On the other hand, the owl-like airfoil shows the minimum drag coefficient at the angle of attack of 1.5°, however, lift coefficient becomes zero at the angle of attack of approximately -2.5°.

The maximum lift-to-drag ratio of the owl-like airfoil is approximately 23 at the angle of attack of 6.0°, while that of the Ishii airfoil is approximately 17 at the angle of attack of 4.5°. Moreover, a lift-to-drag ratio of the owl-like airfoil is higher than that of the Ishii airfoil for all angles of attack.

In summary, the Ishii airfoil gains intermediate lift-to-drag ratio, has mild behavior of the lift curve, and has minimum drag coefficient smaller than that of the owl-like airfoil in spite of the larger airfoil thickness, and has the minimum drag coefficient when the lift coefficient becomes zero. On the other hand, the owl-like airfoil attains greater lift-to-drag ratio, has nonlinear lift curve, and does not have the minimum drag coefficient at zero lift angle of attack. In the next section, mechanisms of high lift generation, drag reduction at high angles of attack, strong nonlinearity of lift curve, and drag increment at the low angle of attack of the owl-like airfoil are discussed based on the flow-fields and surface pressure coefficients.

![Fig. 3. Computational grid.](image)

![Fig. 4. Lift coefficient. The owl-like (circle) and The Ishii airfoil (diamond).](image)

![Fig. 5. Drag coefficient. Symbols as Fig. 4.](image)

![Fig. 6. Lift-to-drag ratio. Symbols as Fig. 4.](image)
3.2. Averaged flow-fields

Figs. 7 shows the time-averaged flow-fields around the owl-like airfoil with locations of separation (S) and reattachment (R) points. It is noted that the locations of separation and reattachment points in Figs. 7 are estimated based on the averaged skin friction coefficient distributions. In addition, time-averaged surface pressure coefficients as a function of chord-direction locations are given in Fig. 8.

The flow in the suction side separates at approximately \( x/c = 0.7 \) without reattachment at the angle of attack of 0.0° up to 3.0°. On the other hand, the flow on the pressure side separates near the leading edge and reattaches near the center of the airfoil, so that a laminar separation bubble is formed. In this way, the flow-fields, observed in Figs. 7(a), (b), (c), have almost the same features but surface pressure coefficients on the pressure side show different characteristics. As shown in Fig. 8, a suction peak near the leading edge, a pressure plateau in range of the laminar separation bubble, and a sudden pressure recovery near the reattachment points are observed. It is noteworthy that the pressure of the plateau at the angle of attack of 0.0° is negative while that at 1.5° and 3.0° are positive. Considering the owl-like airfoil geometry in a lower surface which is deeply concaved, a pressure plateau in range of the laminar separation bubble leads to lift reduction and drag generation. As a result, the drag coefficient at the angle of attack of 0.0° increases as shown in Fig. 5.

When the angle of attack becomes 3.0° up to 4.5°, flow structures and surface pressure coefficients drastically change. The flow feature on the pressure side changes from separated flow including the laminar separation bubble to the attached flow characterized by the absence of pressure plateau in the surface pressure coefficients. On the other hand, on the suction side, the laminar separation bubble is generated near the trailing edge, so that surface pressure coefficients have relatively flat distribution over the airfoil as shown in Fig. 8. In other words, a contribution of suction side to lift largely increases. As a result, it is found that change of separation characteristic makes the lift curve strongly nonlinear as shown in Fig. 4.

As the angle of attack increase from 4.5° to 6.0°, the suction peak is enhanced, and the laminar separation bubble moves toward leading edge as shown in Fig. 7(d), (e). To understand the impact of the intensity of the suction peak and the location of the laminar separation bubble on the drag coefficient, the surface pressure coefficients as function of the lift direction coordinate \( (C_{p-yL}) \) at the angle of attack of 4.5° and 6.0° are presented in Figure 9. Note that the region of \( y_{L}/c \) at the angles of attack of 4.5° and 6.0° are different because projecting plane areas increase with increasing the angle of attack. Integration of the surrounded area of the surface pressure coefficients as function of \( y_{L} \) corresponds to pressure drag. From Fig. 9, integrations of \( C_{p-yL} \) plot at the angles of attack of 4.5° and 6.0° are almost same, so that pressure drag of the both angle of attack are almost the same as shown in Fig. 5.

Moreover, the drag contributed by the laminar separation bubble at the angle of attack of 6.0° is overwhelmed by the intensity of suction peak. It is clear that a suction peak and a laminar separation bubble generally increases drag, but can reduce drag if airfoil geometry consists of an appropriate round leading edge and a flat upper surface.

To clarify the reason why the owl-like airfoil attains higher lift than the Ishii airfoil, surface pressure coefficients of the both airfoils at the angle of attack of 6.0° are compared in Fig. 10. The owl-like airfoil gains higher negative pressure on the suction side over the airfoil than the Ishii airfoil. A significant difference in the surface pressure coefficients is observed in the pressure side. The owl-like airfoil shows much higher positive pressure than the Ishii airfoil. These differences imply that deeply-concaved lower surface of the owl-like airfoil is largely beneficial to lift generation.

![Fig. 7. Time-averaged chord-direction velocity contour.](image)
3.3. Unsteady flow structure

Unsteady flow structure at the angle of attack of 6.0° corresponding to the maximum lift-to-drag ratio condition is discussed. A sequence of instantaneous surface pressure coefficients corresponding to time sequence of flow fields are shown with time-averaged surface pressure coefficients in Fig. 11. In addition, contours of instantaneous spanwise vorticity are illustrated in Fig. 12. The instantaneous surface pressure coefficients follow the averaged surface pressure coefficients up to roughly \( x/c = 0.3 \). Some peaks can be observed in the instantaneous surface pressure coefficients at \( x/c = 0.3-0.4 \) where the shear layer is rolled up and coherent vortex is periodically shed from the shear layer as shown in Fig. 12. Therefore, it should be emphasized in unsteady flow structure that a reattachment point moves backward and forward due to the shear-layer oscillations of the periodic vortex shedding from the shear layer. At the downstream of \( x/c = 0.4 \), as the shed vortices move toward the trailing edge, corresponding peaks also move to the trailing edge. When the shed vortices reach near the trailing edge, a counter-rotating vortex is generated from the pressure side. Subsequently, sudden drop in the instantaneous surface pressure on the pressure side is observed. The variation of the surface pressure coefficients by convection of vortices to the downstream clearly have an impact on time history of lift and drag coefficients as shown in Fig. 13. The instantaneous lift and drag coefficients periodically fluctuate with large amplitude. This is due to periodical shedding of vortices of laminar flow structure.

4. Conclusion

Aerodynamic performance and flow-fields around the owl-like airfoil at a chord Reynolds number of 23,000 were investigated using 2D-laminar flow computations. From the discussions concerning the owl-like airfoil aerodynamics, advantages of the owl-like airfoil are clarified. The owl-like airfoil gains greater lift for all angles of attack considered in this study than the Ishii airfoil though the minimum drag of the owl-like airfoil is higher than that of the Ishii airfoil. This is because of the deeply concaved lower surface of the owl-like airfoil. For airfoils that have the deeply concaved lower surface, the laminar separation bubble is generated on the pressure side and leads to lift reduction and drag generation at low angles of attack if the surface pressure does not sufficiently recover. The suction peak and the laminar separation bubble can reduce drag if airfoil geometry consists of an appropriate round leading edge and a flat upper surface. Thickness of an airfoil with a deeply concaved lower surface and a flat upper surface becomes thin. Therefore, a new airfoil should be designed with considering relationship between thickness and rigidity of the airfoil, and geometric characteristics of the airfoil that can gain higher lift-to-drag ratio. Nonlinearity of the lift curve is caused by the change in separation characteristics: the change from the flow with trailing edge separation to the flow with laminar separation bubble. Oscillation of the separated shear layer and periodically shedding of coherent vortices from the shear layer make reattachment point move backward and forward, leading to fluctuations of the lift and drag coefficients.
Fig. 11. Instantaneous surface pressure coefficients selected times and time-averaged surface pressure coefficient at $\alpha = 6.0^\circ$.

Fig. 12. Instantaneous contours of spanwise vorticity component around the owl-like airfoil at $\alpha = 6.0^\circ$. (Clockwise : red, counterclockwise : blue)

Fig. 13. Time variation of lift coefficient at $\alpha = 6.0^\circ$.

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