Aerodynamics of Owl-like Wing Model at Low Reynolds Numbers*

Hikaru Aono,1,† Katsutoshi Kondo,1) Taku Nonomura,2) Masayuki Anyo,3) Akira Oyama,4) Kozo Fujii,5) and Makoto Yamamoto6)

1)Department of Mechanical Engineering, Tokyo University of Science, Tokyo 125–8585, Japan
2)Department of Aerospace Engineering, Tohoku University, Sendai, Miyagi 980–8579, Japan
3)Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816–8580, Japan
4)Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252–5210, Japan
5)Department of Information and Computer Technology, Tokyo University of Science, Tokyo 125–8585, Japan

Aerodynamics of an owl-like wing model at low Reynolds numbers ($Re = O(10^{4–5})$) are investigated using large-eddy simulations with high-resolution computational schemes. The airfoil shape of the owl-like wing model is constructed based on a cross-sectional geometry of the owl wing at 40% wingspan from the root. The chord-based $Re$ ranges from $1.0 \times 10^4$ to $5.0 \times 10^4$ and the angle of attack ($\alpha$) varies from 0 to 14 deg. The time-averaged lift ($C_l$) and drag coefficients computed are in reasonable agreement with the results of force measurements. The results computed clarify a nonlinear change in the $C_l$ curve slope, which is due to an increase in the suction peaks in conjunction with the change in type of separation, the formation of a laminar separation bubble (LSB), and pressure recovery on the pressure side. The generation of the LSB on the suction and/or pressure sides at the $Re$ of 2.3 $\times$ $10^4$ and 4.6 $\times$ $10^4$ are seen, while reattachments are observed only on the pressure side at the $Re$ of 1.0 $\times$ $10^4$ due to the camber of the wing. Furthermore, the owl-like wing model demonstrates favorable aerodynamic performance in terms of a maximum lift-to-drag ratio in comparison with several airfoils at the $Re$ range considered. This is due to the strong suction peaks and distribution of surface pressure on the pressure side. It is emphasized that the concave lower surface enhances the time-averaged aerodynamic performance at all of the $\alpha$ even though the LSB is generated and fluctuation in lift history is induced at low $\alpha$.

Key Words: Aerodynamics, Viscous Flows, Low Reynolds Number, Bioinspiration

Nomenclature

- $a$: speed of sound
- $c$: chord
- $C_d$: drag coefficient
- $C_l$: lift coefficient
- $C_f$: friction coefficient
- $C_p$: pressure coefficient
- $e$: total energy per unit volume
- $l/d$: lift-to-drag ratio
- $Ma$: Mach number
- $P_r$: Prandtl number
- $Re$: Reynolds number
- $t$: time
- $th$: thickness of the plate
- $u_\infty$: freestream velocity
- $p$: pressure
- $q$: heat flux vector
- $Q$: second invariant of velocity gradient tensor
- $\gamma$: specific heat ratio
- $\delta$: Kronecker delta
- $\Delta \xi$, $\Delta \eta$, $\Delta \zeta$: grid spacing
- $\kappa$: thermal conductivity
- $\rho$: air density
- $\mu$: viscosity of fluid
- $\tau_{ij}$: stress tensor

© 2020 The Japan Society for Aeronautical and Space Sciences

*Received 29 November 2018; final revision received 6 June 2019; accepted for publication 18 July 2019.
†Corresponding author, aono@rs.tus.ac.jp

1. Introduction

In recent years, engineering communities are paying attention to small unmanned air vehicles (UAVs). The UAVs are potentially used for civilian tasks1) including transportation, communication, agriculture, disaster mitigation, environment preservation and planetary aerial exploration.2) The UAVs typically operate in the low Reynolds number flow regime $Re=O(10^{3–5})$ because of their size and flight velocity. Under the low $Re$ flow conditions, viscous effects of the flow around the airfoil in the aerodynamics of the UAVs3–5) play a more important role than those in the aerodynamics of commercial aircrafts.

Recently, Nagai et al.6,7) presented a preliminary UAV design for the aerial exploration of Mars. Their design was obtained through a multi-objective design optimization process with certain constraints. The configuration and propulsion of the UAV are a fixed-wing and direct-current motor-driven propellers, respectively. The chord and span length of the main wing and flight velocity of the model are 0.63 m, 2.45 m, and 60 m/sec, respectively. Thus, the estimated chord-based $Re$ is approximately $2.7 \times 10^4$. The airfoil shape of the main wing is called the Ishii airfoil.8) Although the maximum lift coefficient $C_l$ and lift-to-drag ratio $l/d$ have been presented using large-eddy simulations (LES) and force measurements in a previous study,8) Nagai et al.7,9) emphasized further improvements in the aerodynamic performance of the main wing in order to build a complete UAV system with sufficient robustness for use on Mars.

Previous investigations10–16) have suggested a variety of
cross-sectional airfoil shapes for aircraft with low flight speed. Particularly, Selig and Guglielmo\textsuperscript{16} developed a high-lift, low-\(Re\) airfoil (S1223) at the \(Re\) of \(2 \times 10^5\), Shyy et al.\textsuperscript{17} presented the S1223 with a thinner thickness than the original one, improving the aerodynamic performance at the \(Re\) of \(7.5 \times 10^4\). Interestingly, Liu et al.\textsuperscript{18} mentioned that the S1223\textsuperscript{19} has the same maximum camber line and thickness coordinates of bird airfoils (i.e., airfoils shaped like those of the seagull and merganser wing).\textsuperscript{18,19})

Birds are experts of gliding flight in the \(Re\) range \(O(10^4-5)\) in the Earth’s atmosphere. Owls,\textsuperscript{21-24} swifts,\textsuperscript{25,26} and eagles\textsuperscript{27} are good examples. They fly in the \(Re\) range \(O(10^4–5)\) based on the mean chord length \(c\) of the wing and the gliding flight velocity \(u_\infty\). Through adaptation to their living environment, the wings of some birds possess unique characteristics, such as leading-edge serration, velvet-like surface and feathers, a trailing-edge fringe, structural flexibility, and unique airfoil shape and planform. Until now, the roles and mechanisms associated with each of the above-mentioned features in bird flight have been actively studied.\textsuperscript{24} Most studies have reported that leading-edge serrations,\textsuperscript{28-30} feathers,\textsuperscript{25,26} fringes,\textsuperscript{23,24,31} the effects of wing flexibility,\textsuperscript{24,32,33} and airfoil shape,\textsuperscript{27,34-37} have a positive influence on aerodynamic performance. Very recently, Ananda and Selig\textsuperscript{37} designed bird-like airfoils at the \(Re\) of \(6.0 \times 10^4, 1.0 \times 10^5,\) and \(1.5 \times 10^5\) for the main wings of UAVs. Even though Ananda and Selig\textsuperscript{37} mainly focused on the airfoil shape, their results have shown the best \(l/d\) and \(C_l\) use in UAVs requiring high wing loading. Moreover, Okamoto et al.\textsuperscript{38} studied the effects of thickness, camber, surface roughness, and leading-edge sharpness on aerodynamic performance at the \(Re\) of \(1.1 \times 10^4\) and \(1.4 \times 10^4\). They found that the roughness of the airfoil surface can increase the maximum \(C_l\) and \(l/d\). Sunada et al.\textsuperscript{39,40} conducted a systematic comparison of the aerodynamic characteristics of many airfoil shapes at the \(Re\) of \(4.0 \times 10^4\). They revealed that either an under-camber of \(5\%\) and sharp leading-edge or proper corrugation could improve the aerodynamics of a wing with a rectangular cross-section. Recently, Winslow et al.\textsuperscript{41} investigated various airfoil characteristics at a \(Re\) of \(10^6-7\) using a two-dimensional (2D) Reynolds-averaged Navier-Stokes (NS) solver with a Sparat-Allmaras turbulence model and a correlation-based laminar-turbulent boundary-layer transition model. They showed that cambered flat-plate airfoils have better \(C_l\) and \(C_d\) characteristics than thick conventional airfoils with a rounded leading-edge when the \(Re\) becomes \(10^4\). Moreover, our previous study\textsuperscript{42} examined the aerodynamics of many airfoil shapes at the \(Re\) of \(2.3 \times 10^4\) using 2D laminar simulations. It has been found that the owl-like airfoil has a higher maximum \(l/d\) than that of the Ishii airfoil\textsuperscript{19} and other airfoil shapes considered. Subsequently, we constructed an owl-like wing model based on the cross-sectional profile of the owl wing at a 40\% wingspan from the root and investigated aerodynamic characteristics at the \(Re\) of \(2.3 \times 10^4\) using LES.\textsuperscript{35} The results proved that the owl-like wing model reached a higher \(l/d\) where compared with conventional thin and thick symmetrical airfoils at the \(Re\) of \(2.3 \times 10^4\). However, the aerodynamics associated with the owl-like wing model at other \(Re\) has remained unclear.

Based on the above-mentioned studies, the current study focuses on the aerodynamics associated with the owl-like wing model enabling a wider \(Re\) range compared to those previously studied. Specifically, the \(Re\) range of the UAV cruise flights in the Earth and Mars atmospheres and the gliding flight of birds in the Earth’s atmosphere (i.e. the \(Re\) ranging from \(1.0 \times 10^3\) to \(5.0 \times 10^3\)). This study utilizes the LES approach in order to accurately handle unsteady flow phenomena (i.e., separation, transition, and reattachment) in this low-\(Re\) flow regime. Experimental force measurements are also conducted to validate the results of LES. Although the simplified owl-based airfoil shape is analyzed this study aims to obtain a detailed understanding regarding flow structures around the owl-like wing model and the interplay between flow structures and aerodynamic performance at a low \(Re\).

2. Materials and Methods

2.1. Flow conditions

This study considers that chord and freestream-based Reynolds numbers (\(Re\)) vary from \(1.0 \times 10^3\) to \(5.0 \times 10^4\) and the angle of attack (\(\alpha\)) changes from 0.0° to 14.0°, respectively. This \(Re\) range covers the level flights of UAVs and the gliding flights of owls.\textsuperscript{23} For computation, the freestream Mach number is set to 0.2. This value is low enough that the compressibility of fluid is negligible. Therefore, the flow field obtained using our simulation is considered to be similar to that with a low freestream velocity. The specific heat ratio and Prandtl number are set at 1.4 and 0.72, respectively.

2.2. Owl-like wing model construction

This study considers the same owl-like wing model as that used in our previous study.\textsuperscript{35} The airfoil geometry is decomposed into upper and lower outlines that are constructed based on the mathematical expressions reported in Liu et al.\textsuperscript{18} The upper (\(z_{\text{upper}}\)) and lower (\(z_{\text{lower}}\)) outlines are calculated based on the camber line (\(z_c\)) and thickness distribution (\(z_t\)) as follows:

\[
z_{\text{upper}}(x) = z_c(x) + z_t(x), \quad z_{\text{lower}}(x) = z_c(x) - z_t(x),
\]

where, \(z_{\text{upper}}(x), z_{\text{lower}}(x), z_c(x),\) and \(z_t(x)\) are the upper and lower surface coordinates and a function of the camber line and airfoil thickness, respectively. The Birnbaum-Glauert camber line\textsuperscript{18}) is used to extract the mean camber line (\(z_c\)) from wing surface measurements and is expressed as follows:

\[
z_c(x) = \frac{z_{c,\text{max}}}{c} \eta(1 - \eta) \sum_{n=1}^{3} S_n (2\eta - 1)^{(n-1)},
\]

where, \(c, \eta = x/c,\) and \(z_{c,\text{max}}\) are the local wing chord length, the normalized chord-wise coordinate, and the maximum camber coordinate, respectively. The thickness distribution (\(z_t\)) is given as follows:

\[
z_t(x) = \frac{z_{t,\text{max}}}{c} \sum_{n=1}^{4} A_d (\eta^{(n+1)} - \sqrt{\eta}),
\]
Fig. 1. (a) Cross-sectional wing geometry and (b) computational grid around an owl-like wing model.

where, \( z_{t, \text{max}} \) is the maximum thickness coordinate (i.e., maximum thickness is \( 2z_{t, \text{max}} \)), \( S_1, S_2, S_3, A_1, A_2, A_3 \) and \( A_4 \) are 3.9733, -0.8497, -2.723, -47.683, 124.5328, -127.0874, and 45.876, respectively. Note that these values for the wings of other birds can be found in Liu et al.\(^{18} \). The maximum thickness coordinates \( (z_{t, \text{max}} \) and \( z_{t, \text{max}} \)) are a function of \( \xi = 2y/b \); where, \( b/2 \) is the semi-span of a wing in the sense of the orthographic projection of the wing. For an owl wing, the following relationships\(^{18} \) are obtained as a function of the location in the span-wise direction:

\[
\frac{z_{t, \text{max}}}{c} = 0.04 [1 + \tanh (1.8\xi - 0.5)],
\]

\[
\frac{z_{t, \text{max}}}{c} = 0.04 / (1 + 1.78e^{1.4}).
\]

Based on Eqs. (1), (2), (3), (4), and (5), the cross-sectional shape based on the owl wing is constructed. According to previous reports\(^{18,23,24} \) and assuming that an owl wing nearly possesses an elliptic lift distribution in the span-wise direction, the inner 40\% of the wing from the root provides half of the lift and is selected. Figure 1(a) shows the cross-sectional owl-like wing model at \( \xi = 2y/b = 0.4 \). The maximum thickness ratio is approximately 0.055 at \( x/c = 0.11 \). This value is similar to that reported in Ananda and Selig.\(^{37} \)

It should be noted that the thickness of the computational model near the trailing-edge (i.e. \( 0.9 < x/c < 1.0 \)) is assumed to be zero, while the thickness of the experimental model is 1.25% \( c \).

### 2.3. Fluid dynamic simulation

#### 2.3.1. Governing equations

This study uses an in-house fluid dynamic solver\(^{43} \) to solve unsteady flow around the wing. Three-dimensional (3D) spatially-filtered NS equations, non-dimensionalized by the freestream density, freestream velocity, and chord length of the wing, are employed as the governing equations in this study. In the non-dimensional form, the governing equations are represented as follows:

\[
\frac{\partial p}{\partial t} + \frac{\partial (\rho u_k)}{\partial x_k} = 0, \tag{6}
\]

\[
\frac{\partial \rho u_k}{\partial t} + \frac{\partial (\rho u_k u_k + p \delta_{kk})}{\partial x_k} = \frac{1}{Re} \frac{\partial \tau_{kk}}{\partial x_k}, \tag{7}
\]

\[
\frac{\partial e}{\partial t} + \frac{\partial ((e + p)u_k)}{\partial x_k} = \frac{1}{Re} \frac{\partial (\rho u_k \tau_{kk})}{\partial x_k} + \frac{1}{(\gamma - 1)P_r Ma^2} \frac{\partial q_k}{\partial x_k}. \tag{8}
\]

where, \( x, u, j; \rho, p, e, \tau_{kk}, \delta \), and \( t \) denote the non-dimensional forms of the positional vector, velocity vector, heat flux vector, density, static pressure, total energy per unit volume, stress tensor, Kronecker delta, and time, respectively. The Reynolds (\( Re \)), Prandtl (\( P_r \)), and Mach (\( Ma \)) numbers are non-dimensional parameters and defined as follows:

\[
Re = \frac{\rho_\infty U_\infty c}{\mu_\infty}, \quad P_r = \frac{\mu_\infty C_P}{\kappa_\infty}, \quad Ma = \frac{U_\infty}{a_\infty}, \tag{9}
\]

where, \( \mu_\infty, U_\infty, a_\infty, C_P, \) and \( \kappa_\infty \) represent viscosity, velocity, speed of sound, constant pressure specific heat, and thermal conductivity, respectively. The subscript \( \infty \) denotes the quantity under freestream conditions. Here, the viscosity is calculated using Sutherland’s law.

#### 2.3.2. Numerical methods

In NS equations, the spatial derivatives of convective and viscous terms, metrics, and Jacobian are evaluated using the sixth-order compact differencing scheme.\(^{44,45} \) At the first and second points off the wing surface, a second-order explicit differencing scheme is used. This study utilizes the LES approach in order to prevent the uncertainty of the results that arise because of modeling boundary layer turbulence. Resolving the boundary layer turbulence is important to accurately simulate unsteady flow phenomena. While additional stress and heat flux terms are appended in an ordinary LES approach, they are not implemented in an implicit LES approach.\(^{36} \) In this study, based on the supposition that a high-order, low-pass filter selectively damps only unresolved high-frequency waves, the implicit LES is adopted. A tenth-order filter\(^{44,47} \) is utilized with a filter coefficient of 0.495. This implicit LES approach has been well validated by Visbal et al.\(^{48,49} \) for several problems, and the results of the implicit LES model have agreed with the experimental data and numerical results with standard subgrid-scale models.

For time integration, the second-order backward differencing scheme is used. This study utilizes the Gauss-Seidel implicit method\(^{51} \) in each time step. The computational time is \( 2.5 \times 10^{-4} \) in non-dimensional time corresponding to the maximum Courant number of approximately 1.4. All computations are conducted using either the supercomputer at the Japan Aerospace Exploration Agency (JAXA) or K supercomputer at RIKEN Advanced Institute for Computational Science (AICS) in Japan.

#### 2.3.3. Computational grids and boundary conditions

The computational grid around the wing is shown in Fig. 1(b). A C-type structure mesh is utilized. The grid coordinates are oriented such that \( \xi \) traverses clockwise around the wing, \( \eta \) follows a span-wise direction, and \( \zeta \) is normal to the wing surface.
to the surface. The outer boundary is positioned 30c away from the wing to reduce its influence on the solution near the wing. The first grid points away from the wing surface are $1.4 \times 10^{-4}c$. There are 615 grid points traversing around the wing in the clockwise ($\xi$) direction, 201 points for the span-wise direction ($\eta$), and 101 points for the direction normal to the surface ($\zeta$), so that the total number is 12,485,115 points. The grid resolution of the suction side in terms of span-wise direction ($/C_{17}$)

5.2. Verification and validation analysis

Grid sensitivity analysis is performed in the case of a $Re$ of $4.6 \times 10^4$ and an $\alpha$ of 6.0 deg. Table 1 shows the number of grid points in each direction. Table 1 also includes a comparison of mean lift and drag coefficients ($C_l$ and $C_d$) among the three grids and shows that the difference among the grids is less than 3%. Moreover, the distribution of mean surface pressure ($C_p$) and friction coefficients ($C_f$) among three grids are compared and confirmed (Fig. 2). Therefore, the intermediate grid is selected for all simulations in this study.

Next, the mean $C_l$ and $C_d$ of numerical simulations as a function of $\alpha$ are compared with the experimental data. The bars shown in Fig. 3 indicate standard deviations in the temporal variation of the aerodynamic coefficients under a quasi-steady-state, and filled symbols with line and open symbols indicate numerical and experimental results, respectively. This shows that the computational results are in acceptable agreement with the experimental data, and depict a qualitative trend with respect to the change in $\alpha$. However, a quantitative difference is observed in $\alpha$ when there is a nonlinear change in $C_l$. This discrepancy most likely comes from the difference in flow conditions at the inlet when comparing the numerical simulations and experiments. Moreover, the $C_d$ of experimental results are slightly higher than those of numerical results. This is most likely because of the difference in the thickness at the trailing-edge when comparing the computational and experimental models, in addition to the different inlet flow conditions. Those points should be addressed in the near future. It is noted that the fluid dynamic solver used in this study has been validated for flows around several wings\cite{8,54,55} and the flat plate\cite{56} in similar $Re$ ranges.

3. Results and Discussion

3.1. Aerodynamic performance and fluid dynamics

Figure 3 shows temporal and span-averaged $C_l$ and $C_d$ as a function of $\alpha$. It is seen that $C_l$ and $C_d$ increase as $\alpha$, except for $C_d$ at low angles of attack (i.e., $\alpha < 3$ deg). Since the airfoil shape is asymmetric, $C_l$ is not zero at $\alpha = 0$ deg. A nonlinear change in the $C_l$ curve with respect to the change in $\alpha$ is presented for all $Re$. The change in $Re$ affects $\alpha$ where the nonlinear change in the $C_l$ curve appears (i.e., $\alpha = 4.5$ deg for $Re = 1.0 \times 10^4$, $\alpha = 3.0$ deg for $Re = 2.3 \times 10^4$, and $\alpha = 1.5$ deg for $Re = 4.6 \times 10^4$, respectively). This nonli-
nearity in the $C_l$ curve slope has also been observed in previous reports $^{8,55,57}$ that studied other airfoils. Mueller and Batill $^{57}$ mentioned that a leading-edge separation bubble induces such transition, which accounts for a sudden increase in $C_l$. It should be noted that such nonlinear $C_l$ phenomenon is a well-known factor of low $Re$ airfoils.$^{3-5}$

Figure 4 plots locations of the separation and reattachment points as a function of $\alpha$. In Fig. 4, L.E. and T.E. denote the leading-edge ($x/c = 0$) and trailing-edge ($x/c = 1$). A distance in the $x/c$ between the separation and reattachment points indicates the length of the LSB. For the suction side of the wing (Fig. 4(a)), the flow starts to separate from the trailing-edge side (i.e., trailing-edge separation). As $\alpha$ increases, the separation point moves from the trailing-edge to the leading-edge. When $\alpha$ becomes larger than 6 deg, the flow separates near the leading-edge (i.e., leading-edge separation). The separated shear layers reattach on the surface when $\alpha$ becomes larger than 4.5 and 6 deg at the $Re$ of $2.3 \times 10^4$ and $4.6 \times 10^4$ respectively, resulting in formation of the LSB. The separated shear layers at the $Re$ of $1.0 \times 10^4$ do not reattach on the surface. While for the pressure side of the wing, the separated shear layers reattach on the surface at all $Re$. The separation points move from the leading-edge to the mid-chord of the wing, while reattachment points move from the trailing-edge to the mid-chord of the wing. The length of the LSB in the chord-direction reduces as $\alpha$ increases. At all $Re$, the flow past the pressure side is fully attached when $\alpha$ is higher than 4.5 deg. Moreover, the separation point at the same $\alpha$ locates at almost the same positions for all $Re$. Thus, the length of the LSB in the chord-wise direction on the pressure side mainly depends on the position of the reattachment point, and the length of the LSB decreases as $Re$ increases.

Now, the possible reasons of the nonlinearity in the $C_l$ curve slope for the owl-like wing model are analyzed and discussed based on the computational results corresponding to $\alpha$ according to Figs. 3 and 4 for each $Re$. Figure 5 visualizes instantaneous flow structures around the wing at two $\alpha$ for the $Re$ of $1.0 \times 10^4$, $2.3 \times 10^4$, and $4.6 \times 10^4$. In Fig. 5, the iso-surface represents the second invariant of the velocity gradient tensor $Q$, its color is the vorticity vector in the chord-direction velocity direction ($\omega_v$), the background contours indicate the magnitude of chord-wise velocity, and T.E. denotes the trailing-edge of the wing. The second invariant of the velocity gradient tensor $Q$ and chord-wise direction velocity $u$ are normalized by the freestream velocity $u_\infty$ and chord length $c$. The shear layers are separated, and these separated layers induce a vortex due to Kelvin-Helmholtz instability in the region of upper wing surface. The vortex induced breaks down after it travels a few percent of $c$. It seems that the flow transits from laminar to a turbulent state. At the $\alpha$ corresponding to the nonlinear change in the $C_l$ curve, the location of vortex shedding from the separated shear layers is found near the upper surface of the wing. Moreover, it is seen that the turbulent vortices travel along the wing surface in the snapshot of the flow around the wing. At the same time, an increase in chord-direction velocity over the suction side of the wing is observed due to the change in the flow structures. Figure 6 shows a comparison of temporal and span-averaged $C_p$ distribution on the wing surface at two $\alpha$ for each $Re$. It is found that the suction peaks are enhanced by either the leading-edge separation in the case of $Re$ of $1.0 \times 10^4$ (Fig. 5(a) and Fig. 6(a)) or generation of the LSB on the suction side in the cases of $Re$ of $2.3 \times 10^4$ and $4.6 \times 10^4$ (Fig. 5(b), (c) and Fig. 6(b), (c)) when the $\alpha$ corresponding to the nonlinearity in the $C_l$ curve slope appears. At the same time, the $C_p$ distributions over the pressure side change and increase. Therefore, the significant increase in suction peak due to either the change of type of separation or reattachment of flow near the trailing-edge and the recovery of $C_p$ on the
large and small, respectively, as $Re$ increases. Moreover, due to the variation in time-averaged $C_t$ and $C_p$, $l/d$ also shows a nonlinear curve with respect to the change in $\alpha$. Table 2 and Fig. 7 summarize the data of maximum $l/d$ reported in relevant studies.\(^{8,13,36–38,41,42,55,59–62}\) The results indicate that the owl-like wing model has favorable aerodynamic performance in the $Re$ range region of interest. It should be noted that at the same $Re$, the experimental $l/d_{\text{max}}$ tends to be smaller than the computational one. This is most likely due to the slight difference in drag force data. Furthermore, the values of $l/d_{\text{max}}$ for the Ishii airfoil,\(^8\) SD7003,\(^5\) and NACA0012\(^5\) listed in Table 2 were obtained using the current LES solver. Thus, we think that the values of $l/d_{\text{max}}$ in Table 2 have a certain consistency.

Figure 8 shows temporal- and span-averaged chord-wise velocity $u$ and surface pressure coefficient $C_p$ distribution for the maximum $l/d$ conditions at each $Re$. In Fig. 8, the symbols of S and R denote the locations of flow separation and reattachment points on the wing surface, respectively. It is observed that the laminar boundary layers separate from the wing surface and separation occurs at different locations among the cases. At the $Re$ of $2.3 \times 10^4$ and $4.6 \times 10^4$, flow reattaches on the suction side, resulting in the formation of LSB. High suction peaks of $C_p$ are seen for all $Re$ conditions. Especially, the suction peak of $C_p$ at the $Re$ of $2.3 \times 10^4$ is remarkably high. For the pressure side, $C_p$ keeps a positive value over most of the surface at all $Re$, hence increasing $C_t$.

In addition, in order to explore the reasons that the owl-like wing model has better performance than other Reynolds number airfoils, we conduct a comparison of flowfields around wings and $C_p$ distribution. Here we select the Ishii airfoil\(^8\) and SD7003 airfoil\(^13,63\) from many existing airfoils for comparison. This is because the Ishii airfoil\(^8\) and SD7003 airfoil\(^13,63\) are known as the airfoil shapes that have good aerodynamic performance under the low $Re$ conditions considered and computational results\(^8,63\) are available. Moreover, we focus on and perform this analysis for the maximum $l/d$ condition at the $Re$ of $2.3 \times 10^4$.

Figure 9 illustrates the comparison of cross-sectional airfoil shapes. The owl-like wing model is thinner than the Ishii airfoil\(^8\) and SD7003 airfoil\(^13,63\). The outline of the pressure side of the owl-like wing model shows a deep concave shape in comparison with that of the Ishii airfoil\(^8\) and SD7003 air-

---

**Fig. 5.** Instantaneous iso-$Q$ surfaces ($Qc^2/u_{\infty}^2 = 125$) colored by chord-wise vorticity around the wing.

pressure side are most likely responsible for the nonlinearity in the $C_t$ curve slope observed in Fig. 3.

The maximum $C_t$ is approximately 1.0 for all $Re$ considered and favorable. After $\alpha$ corresponding to the maximum $C_t$, the mean $C_t$ still maintains a high value although the wing is stalled (see Fig. 3). For most $\alpha$, $C_t$ and $C_d$ become

---

**Fig. 6.** Surface pressure $C_p$ distribution over the wing.
Table 2. Comparisons of $l/d_{max}$ in the $Re$ range (1 $\times$ 10^4 - 6 $\times$ 10^6). CFD and EXP indicate computational fluid dynamics and experiment.

| Name of airfoil shape | Method     | $Re$ $\times$ $10^4$ | $l/d_{max}$ |
|-----------------------|------------|-----------------------|-------------|
| Owl-like wing model (current study) | CFD (3D)   | 1.0                   | 13.3        |
| Owl-like wing model (current study) | CFD (3D)   | 2.0                   | 12.1        |
| Owl-like wing model (current study) | CFD (3D)   | 4.0                   | 9.3         |
| Flat plate ($th/c = 2%$) | CFD (2D)   | 1.0                   | 12.9        |
| Cambered flat plate ($6\%, th/c = 1\%$) | CFD (2D)   | 1.0                   | 15.0        |
| NACA6606$^{(11)}$ | EXP         | 1.0                   | 17.0        |
| NACA8660$^{(12)}$ | EXP         | 1.0                   | 16.0        |
| NACA0012$^{(13)}$ | EXP         | 1.0                   | 4.1         |
| Cambered flat plate ($3\%, th/c = 1\%$) | EXP         | 1.1                   | 7.5         |
| Cambered flat plate ($6\%, th/c = 1\%$) | EXP         | 1.1                   | 9.3         |
| Cambered flat plate ($9\%, th/c = 1\%$) | EXP         | 1.1                   | 10.5        |
| NACA0006$^{(15)}$ | EXP         | 1.2                   | 10.3        |
| Owl-like wing model$^{(16)}$ | CFD (3D)   | 1.2                   | 15.3        |
| Circular arc cambered flat plate ($5\%, th/c = 1.3\%$) | EXP         | 2.0                   | 13.3        |
| NACA0012$^{(17)}$ | EXP         | 2.0                   | 7.5         |
| NACA6403$^{(13)}$ | CFD (2D)   | 2.0                   | 12.1        |
| NACA0003$^{(2)}$ | CFD (2D)   | 2.0                   | 14.8        |
| NACA0006$^{(2)}$ | CFD (2D)   | 2.0                   | 15.0        |
| NACA0009$^{(2)}$ | EXP         | 2.0                   | 15.0        |
| NACA0012$^{(2)}$ | CFD (2D)   | 2.0                   | 12.1        |
| NACA5505$^{(2)}$ | EXP         | 2.0                   | 11.5        |
| Owl-like wing model$^{(2)}$ | CFD (2D)   | 2.0                   | 11.5        |
| Seagull-like wing model$^{(2)}$ | CFD (2D)   | 2.3                   | 12.1        |
| NACA64A204$^{(2)}$ | CFD (2D)   | 2.3                   | 17.0        |
| SD7003$^{(3)}$ | EXP         | 2.3                   | 15.0        |
| Ishii airfoil$^{(3)}$ | CFD (3D)   | 2.3                   | 18.1        |
| Ishii airfoil$^{(4)}$ | EXP         | 2.3                   | 14.9        |
| SD7003$^{(3)}$ | CFD (3D)   | 2.3                   | 14.9        |
| NACA0012$^{(3)}$ | EXP         | 2.3                   | 15.7        |
| Flat plate ($th/c = 2\%$) | CFD (2D)   | 4.0                   | 19.8        |
| A1$^{(3)}$ | EXP         | 4.0                   | 35.1        |
| MA409$^{(3)}$ | EXP         | 4.0                   | 35.2        |
| GM15$^{(3)}$ | EXP         | 4.0                   | 43.0        |
| Eppler61$^{(9)}$ | EXP         | 4.6                   | 14.8        |
| NACA0012$^{(5)}$ | EXP         | 5.0                   | 20.3        |
| NACA6409$^{(3)}$ | EXP         | 6.0                   | 18.1        |
| SD7003$^{(3)}$ | EXP         | 6.0                   | 37.6        |
| A1$^{(3)}$ | EXP         | 6.0                   | 42.5        |
| MA409$^{(3)}$ | EXP         | 6.0                   | 45.1        |
| GM15$^{(3)}$ | EXP         | 6.0                   | 51.7        |
| Bird-like wing model (AS0695)$^{(3)}$ | X-FOIL     | 6.0                   | 54.1        |
| Owl-like wing model with feathers$^{(2)}$ | EXP        | 6.0                   | 10.7        |

Foal$^{(13,63)}$, while the outline of the suction side of the owl-like wing model is relatively similar to that of two wings.

Figure 10 shows the comparison of instantaneous and temporal- span-averaged flow structures around the owl-like wing model, around the Ishii airfoil$^{(8)}$, and around the SD7003 airfoil$^{(63)}$ respectively. Figure 11 plots the comparison of temporal- and span-averaged $C_D$ distribution along the airfoil surfaces. Since we consider the flow conditions corresponding to the maximum $l/d$ condition of each wing, all wings are not at the same $Re$. It is found that fundamental structures of instantaneous and averaged flow structures over the suction side of all wings look similar (see Fig. 10). In terms of the instantaneous flow structures, laminar separation occurs, the spanwise vortex is shed from the separated shear layer, and a hairpin vortex is developed due to breakdown of the spanwise vortex. Additionally, in terms of the temporal- span-averaged flow structures, LSB is observed on the suction side of all wings, the length in the chord-wise direction of the LSB is similar, and the location of LSB is different due to the different location of separation and reattachment points on the suction side. As seen in Fig. 11, a considerable difference in $C_p$ distribution is evident. In comparison with that of the Ishii and SD7003 airfoils, the owl-like wing model shows a lower suction peak and surface pressure in the plateau region and a higher pressure region on the pressure side. This is most likely due to the different airfoil shapes and value of $\alpha$. For similar $\alpha$ conditions, the main characteristics of $C_p$ distribution are almost the same (results are not shown

![Fig. 7](image1.jpg)

**Fig. 7.** Comparison of $l/d_{max}$ of the owl-like wing model and other airfoils as a function of $Re$.  

![Fig. 8](image2.jpg)

**Fig. 8.** Time-averaged chord-wise direction velocity $u$ and $C_p$ distribution for the maximum $l/d$ conditions at each $Re$.  

©2020 JSASS
Fig. 9. Comparison of cross-sectional geometry of wings.

Fig. 10. Comparison of flow structures around wings in the case of maximum $l/d$ at $Re = 23,000$: (a) instantaneous and (b) temporal- and span-averaged data.

here). We find that the shape of the pressure side of the owl-like wing model has a positive influence on lift generation. Furthermore, we believe that the above-mentioned characteristics in $C_p$ distribution of the airfoil surface due to its geometry are possible reasons that the owl-like wing airfoil has better performance than other low-$Re$ airfoils (here, the Ishii airfoil and SD7003 are considered) under the maximum $l/d$ condition and at a $Re$ of $2.3 \times 10^4$.

3.2. Effects of pressure-side flow separation on wing aerodynamics

In this subsection, the effects of pressure-side flow separation on aerodynamics are discussed. Here, flow structures around the wing at the $\alpha$ of 0.0 deg are adopted for analysis. As seen in Figs. 4 and 12, at this $\alpha$, flow over the pressure side presents laminar separation, laminar-to-turbulent transition, reattachment, and generation of LSB due to a deeply concave lower surface for all Re, while there is no LSB generation on the suction side. In Fig. 12, the turbulent kinetic energy TKE is defined as $(u'^2 + v'^2 + w'^2)/(2\rho u^2)$, and TKE$_{\text{max}}$ indicates the maximum TKE along the pressure side of the wing surface.

For all Re, the $C_p$ on the pressure side near the reattachment point shows a positive value and gradually decreases toward the trailing-edge. Those positive $C_p$ regions generated on the pressure side enhance lift generation. Moreover, the magnitude of $C_p$ corresponding to the inside of the LSB is similar, while the magnitude of $C_p$ near the reattachment point and its position vary according to the $Re$. The distribution of TKE$_{\text{max}}$ correlates with that of $C_p$ on the pressure side. Figure 13 shows the instantaneous flow structures around the pressure side of the wing and the power spectral density (PSD) of the chord-wise direction velocity $u$ at each Re. Note that the positions of PSD sampling points for chord-wise direction velocity $u$ correspond to the location of TKE$_{\text{max}}$ with variation in the chord-wise direction. The data are ensemble-averaged in the span-wise direction. Results present the unsteady flow features including the vortex shedding from the separated shear layer and the formation of 3D turbulent vortices. The PSD results shown in Fig. 13 show that $-5/3$ power decay can be observed at $x/c = 0.70$ at the Re of $1.0 \times 10^4$, $x/c = 0.50$ at the Re of $2.3 \times 10^4$, and $x/c = 0.35$ at the Re of $4.6 \times 10^4$, and the flow around the wing from the chord-wise position is judged to be turbulent. It is clear that the flow separation over the pressure side has an impact on the time histories of $C_l$ (see Fig. 14) and the $C_l$ fluctuates at all Re. The amplitude and frequency of $C_l$ fluctuation become smaller and higher as Re increases because of the change in the vortical structures around the wing (see Fig. 13).

4. Conclusion

This paper investigates the flow and aerodynamic characteristics associated with the owl-like wing model under low...
compared to common low-Re curve slope with respect to the change of attains a relatively high maximum. The computational results show that the owl-like wing model and used for improving the pressure side. Those near the trailing-edge and the recovery of pressure on the pressure side. The computational time-averaged measurements. The computational time-averaged $C_l$ and $C_d$ are in reasonable agreement with the experimental results. The computational results show that the owl-like wing model attains a relatively high maximum $C_l$ and higher $l/d$ when compared to common low-Re airfoils, such as SD7003,63) the Ishii airfoil,63) and other airfoils in the $Re$ range between 1.0 x 10^4 and 5.0 x 10^4. Although the flow separation and movements and formation of LSB occur on the pressure side, the concave lower surface improves the time-averaged aerodynamic performance at all $a$ in this low-$Re$ flow regime. Moreover, the authors reveal that the nonlinearity in the $C_l$ curve slope with respect to the change of $a$ is most likely due to the increase in the suction peaks in conjunction with either the change of type of separation or reattachment of the flow near the trailing-edge and the recovery of pressure on the pressure side. Those findings could be the basic characteristics of the owl-like wing model and used for improving the aerodynamic design of fixed-wing UAVs flying in the $Re$ range from 1.0 x 10^4 to 5.0 x 10^4.

Acknowledgments

The authors wish to thank Dr. Tianshu Liu for fruitful discussion and comments. This research used computational resources of the supercomputer at Japan Aerospace Exploration Agency (JAXA) and the K supercomputer provided by AICS through the HPCI system research project (Project ID: hp170215).

References

1) Floreano, D. and Wood, R. J.: Science, Technology and the Future of Small Autonomous Drones, Nature, 521, 7553 (2015), pp. 460–466.
2) Hassanalian, M., Rice, D., and Abdelkefi, A.: Evolution of Space Drones for Planetary Exploration: A Review, Progr. Aerospace Sci., 97 (2018), pp. 61–105.
3) Mueller, T. J. (ed.): Low Reynolds Number Aerodynamics, Vol. 54, Springer Verlag, Berlin, 1989.
4) Mueller, T. J. and DeLaurier, J. D.: Aerodynamics of Small Vehicles, Annu. Rev. Fluid Mech., 35, 1 (2003), pp. 89–111.
5) Shyy, W., Aono, H., Kang, C.-K., and Liu, H.: An Introduction to Flapping Wing Aerodynamics, Cambridge University Press, New York, 2013.
6) Nagai, H., Oyama, A., and Mars Airplane Working Group: Mission Scenario of Mars Exploration by Airplane, The 2013 Asia-International Symposium on Aerospace Technology, Nov. 2013, 08-01-3p.
7) Nagai, H., Oyama, A., and Mars Airplane Working Group: Development of Mars Exploration Aerial Vehicle in Japan, Thirtieth International Symposium on Space Technology and Science, July 2015, 2015-k-46.
8) Anyoji, M., Nonomura, T., Aono, H., Oyama, A., Fujii, K., and Asai, K.: Computational and Experimental Analysis of a High-performance Airfoil under Low-Reynolds-number Flow Condition, J. Aircraft, 51, 6 (2014), pp. 1864–1872.
9) Nagai, H., Anyoji, M., Nonomura, T., Oyama, A., Okamoto, M., Sasaki, G., Matsumoto, T., Yonemoto, K., Kanazaki, M., Sunada, S., Yonezawa, K., Koike, M., Fujita, K., Asai, K., and Fujii, K.: Aerodynamic Challenge to Realize Mars Airplane, Thirtieth International Symposium on Space Technology and Science, Nov. 2015, 2015-k-47.
10) McMasters, J. H. and Henderson, M. L.: Low-speed Single-element Airfoil Synthesis, Technical Soaring, 6 (1979), pp. 1–21.
11) Charmichael, B. H.: Low Reynolds Number Airfoil Survey, NASA CR-165803-VOL-1, Nov. 1981.
12) Lissaman, P. B. S.: Low-Reynolds-number Airfoils, Annu. Rev. Fluid Mech., 15, 1 (1983), pp. 223–239.
13) Selig, M. S., Guglielmo, I. J., Broeren, A. P., and Giguere, P.: Summary of Low-Speed Airfoil Data, Vol. 1, SoarTech Publications, Virginia Beach, 1995.
14) Selig, M. S., Lyon, C. A., Giguere, P., Ninham, C. P., and Guglielmo, J. J.: Summary of Low-Speed Airfoil Data, Vol. 2, SoarTech Publications, Virginia Beach, 1996.
15) Lyon, C. A., Broeren, A. P., Giguere, P., Gopalarathnam, A., and Selig, M. S.: Summary of Low-Speed Airfoil Data, Vol. 3, SoarTech Publications, Virginia Beach, 1997.
16) Selig, M. S. and Guglielmo, J. J.: High-lift Low Reynolds Number Air-
foil Design. *J. Aircraft*, 34 (1997), pp. 72–79.
17) Shyy, W., Klevehering, F., Nilsson, M., Sloan, J., Carroll, B., and Fuentes, C.: Rigid and Flexible Low Reynolds Number Airfoils, *J. Aircraft*, 36 (1999), pp. 523–530.
18) Liu, T., Kuykendall, K., Rhew, R., and Jones, S.: Avian Wing Geometry and Kinematics, *AIAA J.*, 44 (5) (2006), pp. 954–963.
19) Schmitz, F. W.: Aerodynamics of the Model Airplane: Part 1. Airfoil Measurements, NASA TM-X-60976, Nov. 1967.
20) Tobalske, B. W., Hedrick, T. L., Dial, K. P., and Biewener, A. A.: Comparative Power Curves in Bird Flight, *Nature*, 421 (2003), pp. 363–366.
21) Graham, R. R.: The Silent Flight of Owls, *Aeronaut. J.*, 38, 286 (1934), pp. 837–843.
22) Lilley, G. M.: A Study of the Silent Flight of the Owl, AIAA Paper 1998-2340, June 1998, pp. 1–6.
23) Bachmann, T., Blazek, S., Erlinghagen, T., Baumgartner, W., and Wagner, H.: *Burn Owl Flight*, Springer, Berlin, 2012, pp. 101–117.
24) Wagner, H., Wenger, M., Klaas, M., and Schröder, W.: Features of Owl Wings That Promote Silent Flight, *Interface Focus*, 7 (2017), 20160078.
25) Lentink, D. and de Kat, R.: Gliding Swifts Attain Laminar Flow over Rough Wings, *Plos One*, 9, 6 (2014), e99901.
26) van Bokhorst, E., de Kat, R., Elsinga, G. E., and Lentink, D.: Feather Roughness Reduces Flow Separation during Low Reynolds Number Glides of Swifts, *J. Exp. Biol.*, 218, 20 (2015), pp. 3179–3191.
27) Carruthers, A. C., Walker, S. M., Thomas, A. L. R., and Taylor, G. K.: Aerodynamics of Aerofoil Sections Measured on a Free-flying Bird, Proceedings of the Institution of Mechanical Engineers, Part G, *J. Aerospace Eng.*, 224 (2009), pp. 855–864.
28) Sodeeman, P. T.: Aerodynamic Effects on Leading-edge Serrations on a Two-dimensional Airfoil, NASA TM-X-2643, Sep. 1972.
29) Ito, S.: Aerodynamic Influence of Leading-edge Serrations on an Airfoil in a Low Reynolds Number: A Study of an Owl Wing with Leading-edge Serrations, *J. Biomech. Sci. Eng.*, 4 (2009), pp. 117–123.
30) Rao, C., Ikeda, T., Nakata, K., and Liu, H.: Owl-inspired Leading-edge Serrations Play a Crucial Role in Aerodynamic Force Production and Sound Suppression, *Bioinsipir. Biomim.*, 12 (2017), 046008.
31) Jaworski, J. W. and Peake, N.: Aerodynamic Noise from a Poroelastic Wing, *J. Aircraft*, 2009–3, 19 (2010), pp. 1941–1942.
32) Fujii, K., and Yamamoto, M.: Analysis of Owl-like Airfoil Aerodynamics at Low Reynolds Number Flow over a Two-dimensional Airfoil at Low Reynolds Numbers, ASME 2013 Fluids Engineering Division Summer Meeting, American Society of Mechanical Engineers, July 2013, pp. 1–6.
33) Kondo, K., Aono, H., Nonomura, T., Oyama, A., Fujii, K., and Yamamoto, M.: Large-eddy Simulations of Owl-like wing under Low Reynolds Number Conditions, ASME 2013 Fluids Engineering Division Summer Meeting, American Society of Mechanical Engineers, July 2013, pp. 1–6.
34) Kondo, K., Aono, H., Nonomura, T., Anjoji, M., Oyama, A., Liu, T., Fujii, K., and Yamamoto, M.: Analysis of Owl-like Airfoil Aerodynamics at Low Reynolds Number Flow, *Trans. JSASS Aerospace Technology Japan*, 12, iss29 (2014), pp. Tk.35–Tk.40.
35) Liu, X. and Liu, X.: A Numerical Study of Aerodynamic Performance and Noise of a Bionic Airfoil Based on Owl Wing, *Adv. Mech. Eng.*, 2014 (2014), 1–10.
36) Ananda, G. K. and Selig, M. S.: Design of Bird-like Airfoils, AIAA Paper 2018-0310, Jan. 2018.
37) Okamoto, M., Yasuda, K., and Azuma, A.: Aerodynamic Characteristics of the Wings and Body of a Dragonfly, *J. Exp. Biol.*, 199 (1996), pp. 281–294.
38) Sunada, S., Sakaguchi, A., and Kawakita, K.: Airfoil Section Characteristics at a Low Reynolds Number, *J. Fluids Eng.*, 119 (1997), pp. 129–135.
39) Sunada, S., Yasuda, T., Yasuda, K., and Kawakita, K.: Comparison of Wing Characteristics at an Ultra-low Reynolds Number, *J. Aircraft*, 39, 2 (2002), pp. 331–338.
40) Winslow, J., Otsuka, H., Govindarajan, B., and Chopra, I.: Basic Understanding of Airfoil Characteristics at Low Reynolds Numbers (10^5–10^6), *J. Aircraft*, 55 (2018), pp. 1050–1061.
41) Kondo, K.: Computational Comparative Study for Design of Low Reynolds Number Airfoil, Twenty-ninth Congress of the International Council of the Aeronautical Sciences, Sep. 2014, 0818–1–10.
42) Fujii, K. and Obayashi, S.: High-resolution Upwind Scheme for Vortical-flow Simulations, *J. Aircraft*, 26, 12 (1989), pp. 1123–1129.