Low \( \Re \), High \( \alpha \) Aerodynamics with Controlled Wing Kinematics

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ABSTRACT

Numerical simulations of an ultra low Reynolds number (\( \Re \)), high angle of attack (\( \alpha \)), thin, two-dimensional airfoil representative of insect wings, have been conducted for \( \Re \) range, \( \sim 500-5000 \), and two values of \( \alpha \) (\( \sim 30^\circ \) and \( \sim 45^\circ \)). The time-accurate, unsteady simulation results are analyzed and the phase relations of the leading edge and trailing edge vortex (LEV/TEV) dynamics to cyclical lift variation are established. The results show the present fixed wing undergoing a high-lift phase during each lift cycle. At moderately high \( \alpha \), the LEV dominates, and at higher \( \alpha \) the LEV and TEV are equally dominant. The Strouhal number for all the cases considered is close to that of the Karman vortex shedding, a significant departure from some of the previous high \( \Re \) results. We propose that, by matching the wing beat frequency of biomimetic micro air vehicles that incorporate wing kinematics to that of the corresponding Karman vortex shedding frequency, the wing can avoid operating in the low lift phase, explaining, at least in part, the high lift associated with insect flight.

Introduction

Low Reynolds number, unsteady aerodynamics of thin cambered wings are of current interest because of technological applications such as micro air vehicles (MAV). High lift associated with insect flight, not predicted by conventional quasi-steady aerodynamics, has been a fascinating subject for many researchers. Gaining a thorough understanding of insect wing aerodynamics and incorporating their desirable features into MAV design have become one of the critical technologies for biomimetic MAV development. Several aerodynamic models have been proposed to explain lift generation during the cyclic motion of the insect wing. Forward flight, requiring both lift and thrust, has been more easily analyzed than hovering flight. Studies on tethered live animals have been conducted to measure forces and visualize flow patterns. Experimental studies using models having basic wing kinematics such as heaving, flapping and pitching, have also been undertaken.

Some insects execute the “clap-and-fling” mechanism (Weis-Fogh mechanism) during the wing beat cycle \([1,2,3]\). Insects that execute this mechanism start the stroke cycle with the wing surfaces in contact with each other. The beat cycle starts with the wing leading edges moving apart as if the wings were hinged at the trailing edges. After reaching the maximum angular displacement, the two wings separate at the trailing edges, change the sense of rotation and linear motion, and come together with the leading edges coming in contact first. A motion, in reverse to the fling motion is executed with the leading edges forming the hinge. The wings then rotate about the leading edge hinge in a clapping motion to complete the cycle. Weis-Fogh \([1]\) and Lighthill \([2]\) modeled the corresponding aerodynamics in terms of bound vortices using inviscid theory. Lighthill also applied a correction factor for viscous effects. Even though their model satisfied the Kelvin-Helmholtz theorem, according to which the circulation should remain zero, Weis-Fogh pointed out that the effect is not the common Magnus effect since the lift produced during the fling is in the opposite sense to that would be created by the Magnus effect. Other unsteady mechanisms are suggested for the creation of circulation of the right sense. The Weis-Fogh-Lighthill theory generated great interest at the time; however, closer examination revealed its limitations, not including the effect of viscosity being...

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the most obvious. At the Reynolds numbers of interest ($Re \sim 1000$), inviscid theories are not likely to be reliable. Later, Maxworthy [3] performed experiments to explain the Weis-Fogh mechanism in terms of the interaction of the leading edge vortices from the wings as they fling apart.

Not all insects execute the clap-and-fling motion described above. Dickinson et al. [4,5,6] recently proposed the “delayed-stall-rotational-lift-wake-capture” mechanism to explain lift generation during all phases of the wing beat cycle. During the up- and down-strokes, a leading edge vortex (LEV) forms and stays attached to the surface creating lift (“delayed stall”). As the wing approaches the end of each stroke, it rotates in preparation for the following stroke; this rotation coupled with the translation relative to the surrounding air creates lift (“rotational lift”). Finally, “wake capture” denotes the augmentation of the relative velocity and the resultant lift due to the wing wake flow as the wing reverses the direction of its linear motion at the ends of the strokes. Dickinson’s model is an improvement over previous models due to its ability to explain lift generation during all phases of the wing beat cycle in terms of known aerodynamic phenomena [7].

A few theoretical and computational studies also have been conducted. Vest and Katz [8] solved the potential flow equations of a flapping wing in an inertial reference frame. Thrust and lift produced during the wing beat cycle were obtained. The authors provide a discussion of the limitations of applying the classical Kutta condition to the flapping wing problem. Wang’s [9] two-dimensional (2D) computations of an airfoil of elliptic cross section in flapping motion showed how insects can create sufficient lift to hover. Kunz and Kroo’s [10] 2D simulations of ultra-low Reynolds number airfoils showed some interesting features of the flow in this flow regime. Three-dimensional (3D) computational fluid dynamics simulations of flapping wing aerodynamics have been attempted by Chasman and Chakravarthy [11], Emblemsvag, et al. [12], and Liu and Kawachi [13].

Several computational studies are in progress to understand the fluid-structure interaction that is inherent in insect flight. One approach is to model the wing as a membrane that deforms when subjected to fluid flow. Visbal and Gordnier [14] performed numerical simulation of boundary layer interaction with a flexible panel. A high order implicit method helped retain high accuracy in the presence of deforming meshes. Limit cycle oscillations appeared to originate from the coupling of Tollmiien-Schlichting (T-S) waves and higher-mode flexural waves on the elastic panel.

For aircraft applications, Gordnier [15] investigated limit cycle oscillations of a cropped delta wing using a procedure that coupled a Navier-Stokes solver with a nonlinear finite element solver [16], and obtained better agreement with experiments compared to results from a previous linear structural model. Shyy et al. [17] and Lian, et al. [18] investigated the interaction of deformable membrane wings and air flow under MAV flight conditions.

Experimental studies of low Reynolds number airfoils include those of Torres and Muller [19], Maxworthy [3], and Chasman and Chakravarthy [11]. Frampton et al. [20] examined passive aeroelastic tailoring to optimize flapping wing performance. Low aspect ratio wings made of mylar skin and carbon fiber spars and ribs were tested to determine thrust and power dependence on the phase angle between and bending and torsion and the bending-torsion frequency ratio. Excitation was provided in only one degree of freedom, but aeroelastic tailoring enabled bending and torsion modes to be excited.

Anderson et al. [21] investigated thrust producing mechanisms of harmonically oscillating foils by flow visualization at $Re = 1100$, and by force measurements at $Re = 40,000$. Both leading edge and trailing edge vortices have been observed, and their interaction has been identified as a factor in thrust generation and the formation of a reverse Karman vortex street. Most of the studies of leading and trailing edge vortices (LEV/TEV) have been done on oscillating airfoils, and the interpretations of the results tend to tie these vortices to the forced oscillations. While the oscillations might accentuate the vortices, results of the present study suggest that unsteady vortex shedding from the leading and trailing edges similar to the Karman vortex shedding are present in non-oscillating foils, and oscillatory behavior of the lift and drag curves can be explained in terms of the dynamics of the LEV/TEV. It appears that the high instantaneous angles-of-attack associated with the oscillations might be the reason for the strong presence of the LEV/TEV in such situations. Since a large number of the previous studies have been driven by the need to understand fundamental phenomena, and not by the desire to adapt insect wing features in vehicle design, the effect of airfoil shape was not emphasized. The NACA laminar flow airfoils and the low Reynolds number airfoil of Kunz and Kroo [10] are two examples in which the airfoils have been optimally designed for low Reynolds number conditions.

Vortical signatures of an airfoil in plunging and pitching modes have been investigated by Freymuth [22]. The vortex pattern in the thrust-generation mode
was shown to induce a wake velocity in a sense opposite to that of the Karman vortex street. Koochesfahani’s [23] work on NACA 0012 airfoil also examined the vortical pattern in the wake, and thrust generation, when oscillations by pitching the airfoil about the quarter chord point were imposed. A wake vortex pattern opposite to that of the KVS was observed with the wake behaving as a “jet” and producing thrust instead of drag for frequencies above a threshold. The corresponding mean velocity profiles showed a momentum excess in the wake indicating thrust.

Gursul and Ho [24] investigated the effect of unsteady free stream velocity and reported that lift coefficient increased by an order of magnitude by imposing oscillations in the free stream velocity, but keeping its direction unchanged. Phase relationship between the leading edge vortex dynamics and lift variation was used to explain increase in lift coefficient. Trail vortices were not cited as playing a part in the vortex dynamics discussed by the authors based on results from water tunnel flow visualization experiments. However, their flow visualization pictures leave some doubt about the sense of vortex rotation in some frames, and it is possible that the corresponding vortices originated at the trailing edge (see frame for $t/T = 0.5$ s, Fig. 2, Ref. 24). Because of the limitations on temporal and spatial resolution in flow experiments, it is not always possible to accurately pinpoint the original and evolution of the vortices. Numerical simulations with sufficient temporal and spatial resolution, therefore, provide a complementary tool in tracking the vortices.

McAlister and Carr’s [25] water tunnel experiments on a NACA 0012 airfoil explored dynamic stall by imposing large amplitude pitching oscillation about the static stall angle. An observation of theirs relevant to the present work is that Karman vortex shedding was present even at low angles-of-attack in the static case.

Visbal and Shang [26] did numerical computations of a pitching NACA 0015 airfoil. The basic vortical structure of their studies agreed with experimental flow visualization for chord-based Reynolds number $\approx 45,000$. A leading edge vortex, a shear layer vortex and a trailing edge vortex were identified. The authors correctly observed that the counter clockwise vortex originating in the lower surface boundary layer was shed into the wake, while the clockwise vortex remained on the upper surface, as also observed in the experiments of Walker, et al. [27]. Visbal [28,29] discussed the dynamic stall flow features for laminar and turbulent conditions. Effects of pitch rate and pitch axis location were examined. Morgan and Visbal [30] conducted numerical simulation of unsteady, laminar three-dimensional separation on a pitching wing. Dynamics stall vortex behavior was analyzed by comparing 2D and 3D simulations. 3D symmetric plane and 2D solutions departed as the pitch angle increased.

In this work, we use computational fluid dynamics tools to simulate low Reynolds number, unsteady aerodynamics that incorporate geometries and kinematics representative of insect wings. Leading edge and trailing edge vortex (LEV/TEV) dynamics, span-wise flow features, dynamic camber variation during the wing beat are of particular interest. One of the objectives of the present work is to demonstrate that much of the observations can be explained in terms of the dynamics of the leading edge and trailing edge vortices, and these vortices play a dominant role even in cases in which forced wing oscillations are not imposed. A cambered, zero thickness airfoil is used in this work to establish that the leading edge and trailing edge vortices form alternatively and shed to form the vortex street, the strengths of the vortices dependent on the angle-of-attack. The airfoil was modeled after the North American cicada wing (Fig. 1), and the sharp leading and trailing edges accentuate the vortices originating at these locations.

**Low-\(\alpha\) Results**

For the first geometry, an airfoil with an elliptic leading edge and a gradually tapering trailing edge was modeled. The airfoil chord length, $c$, was 30 cm and the maximum thickness was 1.4 cm, approximately 5% of $c$. When the free stream flow direction was tangential to the camber line at the leading edge, the angle between the chord line and the free stream flow direction (angle-of-attack) was $11^\circ$. The computational fluid dynamics package FLUENT [31] was used for the CFD simulations.

For the first set of cases, a parabolic flow domain having 42,026 cells was used. The cells were distributed with a larger number close to the airfoil surface and fewer away from it. This set of runs consisted of eight cases for angles-of-attack ranging from $-3^\circ$ to $18^\circ$, in increments of $3^\circ$. The section lift and the drag coefficients defined, respectively, by Eqs. 1 and 2 below, were calculated.

\[
\begin{align*}
    c_l &= \frac{L}{q_s c} \\
    c_d &= \frac{D}{q_s c}
\end{align*}
\]

where, $L$ and $D$ are the lift and drag forces per unit span, respectively, $\rho$ is the density of the fluid, $U_s$ is the free stream velocity and $c$ is the wing chord length.
The section lift coefficient of a thin symmetric airfoil is given by 
\[ c_l = 2\pi\alpha \] where, \( \alpha \) is the angle-of-attack in radians. The simulation results were compared with the above theoretical values of \( c_l \). For small positive values of the angle-of-attack, the \( c_l \) values agreed well with thin airfoil theory. Outside this range, the \( c_l \) values were lower than the theoretical value, indicating flow separation, which was confirmed by velocity vector plots. These comparisons served to validate the present computations. The velocity vector plots showed flow separation on the lower surface for negative values of \( \alpha \) and, as \( \alpha \) increased, the flow started separating toward the upper surface trailing edge in the form of a small bubble, but it reattached itself ahead of the trailing edge.

With the knowledge gained from the previous case studies, two new airfoil sections were created for further simulations. A thin cambered airfoil has the necessary low \( Re \) characteristics that can be used to advantage in MAVs. A circular-arc airfoil with negligible thickness and a thin airfoil with an elliptic leading edge and a gradually tapering trailing edge, both having the same camber, were modeled. The choice of these two airfoil shapes differing in thickness, but identical in other respects, provided a means of further evaluating the effect of thickness on the low \( Re \), high-\( \alpha \) unsteady flow field. The chord length, \( c \), was 36.5 cm for both cases, and the maximum thickness of the latter airfoil was 1.825 cm (0.05c). Seven cases were run with \( \alpha \) ranging from 8.3° to 44.2°. \( c_l \) values from the small-\( \alpha \) simulations were compared to those from thin airfoil theory. The close agreement between the \( c_l \) values from these simulations and the thin airfoil theory for small values of \( \alpha \) served to further validate the CFD procedure.

**Biomimetic Wing Models**

In order to investigate the low \( Re \) high-\( \alpha \) behavior, a 2D wing and a 3D wing were modeled after the North American cicada wing (Fig. 1). For the 2D cases given below, the cicada wing camber line is approximated as a circular arc. When the free stream approaches tangential to the surface at the leading edge, the angle-of-attack, \( \alpha = 9.4° \). The cicada wing being thin and membrane-like, thickness effect was not included in these runs. The 2D wing geometry, not shown separately, can be seen in the contour plots that follow.

The cicada wing is thin (thickness-to-maximum chord ratio \( \sim 0.02 \)), has a slight camber, and a slight curvature in the span-wise direction. The hind wing can rotate about the leading edge, which forms a common line of contact with the forewing trailing edge. It appears that one of the functions of the hind wing is to act as a control surface to control camber during the stroke cycle. It may also produce thrust the same way a pitching airfoil does [22,26]. As discussed by Dickinson, et al. [6], the insect wing undergoes large changes in orientation during pronation and supination in order to provide optimum lift and thrust during the entire stroke cycle. The other interesting feature to note is the layout of the spar-and-rib structure. Unlike aircraft wing, it appears that the natural wing lends itself to large flexure, which has been observed in experiments with live insects. For the 3D wing shown in Fig. 2, the planform was approximated as a semi-ellipse with an aspect ratio of 3. Even though the cicada has hind wings (the right one is shown in Fig. 1), the 3D model shown in Fig. 2 has only the forewing.

![Figure 1. The North American cicada forewings and the right hind wing. Note that the forewing and the hind wing are attached along the trailing edge and the leading edge, respectively.](image1)

![Figure 2. 3D Elliptic wing modeled after North American cicada wing.](image2)

**Numerical Algorithm**

The FLUENT [31] numerical simulation package has many options for space and time discretization. For the present laminar flow case, all the available space discretization schemes could be used without perceptibly influencing the solution. For space discretization, the second-order upwind scheme [32] was used. The equations are solved sequentially, first the momentum equations, and then the conservation of
mass equation. A point implicit linear equation solver is used in conjunction with an algebraic multigrid method to solve the resultant scalar system of equations. Most of the results presented in this paper are based on an unsteady, first-order implicit method for time discretization. The discretization in the general form for variable $\phi$ is as follows.

$$\frac{\phi^{n+1} - \phi^n}{\Delta t} = F(\phi^{n+1})$$ \hspace{1cm} (3)

where $n$ represents the time level and $\Delta t$ represents the time step size. The second-order accurate implicit form for time discretization, used in selected cases to establish numerical accuracy, is given by

$$\frac{3\phi^{n+1} - 4\phi^n + \phi^{n-1}}{2\Delta t} = F(\phi^{n+1})$$ \hspace{1cm} (4)

The computational domain with a parabolic inflow boundary and planar outflow boundary, extended approximately 10 chord lengths to the front, rear, top, and bottom. The production runs of the biomimetic wing employed ~110,000 quadrilateral cells finely distributed close to the airfoil surface, and coarser towards the outer boundaries. Prior to the production runs were made, the grid quality was checked using several criteria [31].

The numerical schemes available in the software package used in the present study has been used in numerous other studies, including those by the present authors, and their behavior such as numerical diffusion has been well-documented. Therefore, code validation for the present work focused mainly on validating the procedures relevant to the present work. As a part of this effort, flow simulation over a conventional NACA 0012 airfoil at low angle-of-attack and high Reynolds number was done, and the lift curve was compared with published airfoil data. The comparison showed excellent agreement. Code validation for airfoil type problems has also been done in our earlier work, and the results have been documented [33]. Additionally, one case was run with three segments, each for 2.5 seconds of flow time. Second-order implicit scheme with step size $\Delta t = 0.001$ s was used in the first segment. For the second segment, the time integration scheme was changed to first-order implicit, and for the third segment, first-order implicit scheme was used, with the step size halved to 0.0005 s. The lift curve from these runs is shown in Fig. 3. Clearly, there is no noticeable difference among the three segments of the lift curve corresponding to the three different finite difference schemes, indicating that the results are not influenced by the choice of the numerical integration scheme.

Low $Re$, High-$\alpha$ Results

The simulations were done for conditions that correspond to those on the surface of Mars, chosen to investigate the feasibility of developing an Entomopter for Mars missions. See Ref. [34] for details. The chord-based Reynolds number was varied in the 510-5100 range, representative of insect flight regime. A high angle-of-attack value was used to characterize the formation and evolution of the leading edge and trailing edge vortices (LEV/TEV). These time-accurate simulations were done using a very fine mesh (~110,000 cells) and small integration time step (0.001 s). Both the mesh size and the time step were varied and the corresponding simulation results were compared to ensure that the results can be treated as independent of mesh size and time step size.

![Figure 3. Effect of varying time-integration scheme and time step size](image-url)

In order to establish the phase relationship between the $c_l$ variation and the dynamics of the leading edge and trailing edge vortices (LEV/TEV), results from one case are presented in Figs. 4 and 5. The corresponding chord-based Reynolds number, $Re_c = 2040$ and the angle-of-attack, $\alpha = 29.4^\circ$. The lift curve (Fig. 4) spans slightly more than one cycle with a period, $\tau \approx 0.3$ s. A Strouhal number calculated using the frequency, $f$ (\(1/\tau\)), the chord length, $c$ and the free stream velocity $U_\infty$ is given by the following expression.

$$St = \frac{fc}{U_\infty}$$ \hspace{1cm} (5)

For all the cases considered in this work ($Re_c = 510-5100$ range), the Strouhal number, $St \approx 0.2$, close to that of Karman vortex shedding [35]. Points labeled 1 – 10 on the $c_l$ curve in Fig. 4 indicate instants for which
contour plots are given in the 10 figures (5-i – 5-x) that follow. Note that the flow times are given in the inset text in Figs. 5-i – 5-x. Figure 5-i shows the beginning of the cycle. The TEV has just detached from the trailing edge and the LEV is just beginning to form. The lift at this instant is near its trough. The following three figures show the growth and downstream convection of the LEV and the corresponding rise in c_l. In Fig. 5-ii, the LEV is weak, indicated by the light green hue towards the front on the top surface. The relative strength of the vortices can be observed in Figs. 5-ii – 5-iv, from the rapidly changing color, the strong vortex core indicated by dark blue. In Fig. 5-v, the LEV has nearly detached from the surface after being convected downstream towards the trailing edge, and as it detaches, c_l falls to its value indicated by Point 5 in Fig. 4. The lift then rises momentarily, probably, as a result of the weaker secondary leading edge vortex present in Fig. 5-v. Figures 5-vi – 5-viii show the TEV-dominated phase of the lift cycle in which the TEV forms, grows and detaches, and the lift falls to its lowest value shown by Point 8 in Fig. 4. The cycle then repeats, starting with the formation of the LEV at the leading edge.

Several important flow features can be observed from these results. At this high angle-of-attack, the wing generates large amount of lift, indicating that extrapolation of high Re results would be erroneous, especially the catastrophic stall pattern of conventional high Re airfoils is not observed in the present cases. The other feature is the large amplitude of the c_l oscillations with time. The frequency and amplitude of the lift and drag variations depend on the angle-of-attack and Re_c as will be discussed later.

Figures 6-15 show lift and drag coefficient variations for two values of α (44.2° and 29.4°) and five values of free stream velocity ranging from 1.4 m/s (Re_c = 510) to 14 m/s (Re_c = 5100). This set of c_l and c_d plots reveal several interesting characteristics, not emphasized in previous works of similar nature, of low Reynolds number, high angle-of-attack aerodynamics. The plots show that there are distinct frequencies associated with each case, and both the lift and drag variations have fairly large amplitudes. The salient features are summarized in Table 1. The Strouhal number has been calculated in two ways, one based on the chord length (A) and the other based on the projected length normal to the free stream (B). These results indicate that, for these cases also, the flow is dominated by the formation and shedding of the leading edge and trailing edge vortices (LEV/TEV), as in the previous case. The LEV forms at the leading edge, stays attached to the top surface and grows as it convects downstream. During this phase, the airfoil has a high c_l value, and then it drops as the vortex detaches from the surface, leading to the low c_l phase of the cycle. The low c_l phase continues during the formation, growth and detachment of the TEV. The c_d variation has a phase difference of approximately 180° from the c_l variation. From the summary results given in Table 1, several useful design guidelines can be drawn. For example, for Re_c = 5100 the dominant frequency, f ≈ 7.23 Hz. To investigate the relationship to the well-known Karman vortex shedding (KVS) from bluff bodies, the Strouhal number, defined earlier in Eq. (5) was calculated, and its values shown in Table 1 are close to that of the KVS. Therefore, the flow in the present low Re high-α simulations is closely related to flow over bluff bodies at low Reynolds numbers, manifested by the similarity in the alternate shedding of the leading and trailing edge vortices at the KVS frequency. Another important observation is that the cases in the above Reynolds number range do not yield a steady state solution, indicating that such a solution will violate the flow physics. A similar observation has also been made by Kunz and Kroo [10]. Note that, for the Reynolds number range of this study, the flow cannot be approximated as being dominated by viscous forces, a valid assumption for Re_c < 1, nor can it be approximated as being dominated by inertia forces, a common assumption for large values of Re_c. For this reason, analytical results are not available in the literature for this flow regime [36].

If the wing stroke frequency were to match the dominant frequency of the lift curve (also the KVS frequency), the low c_l phase can be avoided, and the airfoil can always stay in the high c_l and c_d phase. Note that the c_l/c_d ratio varies over the range ~3.273-20.8, indicating the benefits of tailoring the stroke frequency to the LEV/TEV cycle. In micro air vehicle (MAV) design, this would require establishing the relationship between the flow velocity and the frequency of the LEV/TEV dynamics, so that, by choosing appropriate stroke cycle frequency, the wing would operate in the high c_l mode during the entire cycle. A review of literature indicates that similar cyclical variation of c_l has been observed in experiments and computations by Zaman et al.[37] and computations by Kunz and Kroo[10]. However, the Reynolds number range of Zaman et al. [37] was much higher in which the flow was turbulent. Their flow frequency was an order of magnitude lower than the KVS frequency. The present results and those of previous studies suggest that the ability to have variable beat frequency depending on flight conditions to improve performance should be a design goal. Formulating control laws that take into account the above effects should, therefore, be part of the MAV development effort.
Conclusions

The present results reveal several features of high angle-of-attack low Re (~500-5000) aerodynamics that haven’t been systematically investigated in previous works. The formation of the leading edge and trailing edge vortices (LEV/TEV) and their growth and transport have been investigated for \( \alpha \) and \( \text{Re} \) variations over a wide range, and the close relationship to the classical Karman vortex shedding is clearly established. The phase relationship between the vortex dynamics and the lift curve show distinct roles played by the LEV and TEV. Lift is high during the phase when the LEV forms and stays attached to the top surface. This is followed by the next phase during which the LEV is detached and the TEV forms at the trailing edge and sheds into the wake. Results from the cases considered in this paper indicate that by carefully choosing the Reynolds number regime and the wing kinematics during the wing beat cycle, especially beat frequency, lift can be increased to meet the demands of an Entomopter for Mars missions and a biomimetic micro air vehicle (MAV) for terrestrial applications. The results can be used to develop guidelines for developing biomimetic micro air vehicles, and more cases are being run to generalize the observations and gain further understanding of mechanisms involved. Work is in progress for simulations of a biomimetic 3D wing. Additional factors such as acceleration and deceleration and wing rotation at the ends of the strokes need to be considered to further understand and utilize the desirable features of insect flight.

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References

with a Navier-Stokes Solver,” AIAA-2001-2853.
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<td>0.64</td>
<td>0.63</td>
<td>0.52</td>
<td>0.52</td>
<td>0.51</td>
<td>0.25</td>
<td>0.45</td>
<td>0.44</td>
<td>0.44</td>
<td>0.36</td>
</tr>
<tr>
<td>Strouhal number (St), A</td>
<td>0.24</td>
<td>0.22</td>
<td>0.21</td>
<td>0.22</td>
<td>0.2</td>
<td>0.33</td>
<td>0.25</td>
<td>0.22</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td>Strouhal number (St), B</td>
<td>0.17</td>
<td>0.15</td>
<td>0.15</td>
<td>0.14</td>
<td>0.16</td>
<td>0.12</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Figure 4. Lift variation with time. $Re_c = 2040$, $\alpha = 29.4^0$

Figure 5-i. Static pressure (Pa) contours. $Re_c = 2040$, $\alpha = 29.4^0$, $t = 33.252$ s

Figure 5-ii. Static pressure (Pa) contours. $Re_c = 2040$, $\alpha = 29.4^0$, $t = 33.292$ s

Figure 5-iii. Static pressure (Pa) contours. $Re_c = 2040$, $\alpha = 29.4^0$, $t = 33.332$ s

Figure 5-iv. Static pressure (Pa) contours. $Re_c = 2040$, $\alpha = 29.4^0$, $t = 33.372$ s

Figure 5-v. Static pressure (Pa) contours. $Re_c = 2040$, $\alpha = 29.4^0$, $t = 33.412$ s
Figure 5-vi. Static pressure (Pa) contours. $R_e = 2040$, $\alpha = 29.4^\circ$, $t = 33.452$ s

Figure 5-vii. Static pressure (Pa) contours. $R_e = 2040$, $\alpha = 29.4^\circ$, $t = 33.492$ s

Figure 5-viii. Static pressure (Pa) contours. $R_e = 2040$, $\alpha = 29.4^\circ$, $t = 33.532$ s

Figure 5-ix. Static pressure (Pa) contours. $R_e = 2040$, $\alpha = 29.4^\circ$, $t = 33.572$ s

Figure 5-x. Static pressure (Pa) contours. $R_e = 2040$, $\alpha = 29.4^\circ$, $t = 33.612$ s
Figure 6. Lift and drag coefficients: $U_\infty = 1.4$ m/s, $\alpha = 44.2$ deg.

Figure 7. Lift and drag coefficients: $U_\infty = 2.8$ m/s, $\alpha = 44.2$ deg.

Figure 8. Lift and drag coefficients: $U_\infty = 5.6$ m/s, $\alpha = 44.2$ deg.

Figure 9. Lift and drag coefficients: $U_\infty = 10.5$ m/s, $\alpha = 44.2$ deg.
Figure 10. Lift and drag coefficients: $U_\infty=14\text{ m/s}, \alpha = 44.2\text{ deg.}$

Figure 11. Lift and drag coefficients: $U_\infty=1.4\text{ m/s}, \alpha = 29.4\text{ deg.}$

Figure 12. Lift and drag coefficients: $U_\infty=2.8\text{ m/s}, \alpha = 29.4\text{ deg.}$

Figure 13. Lift and drag coefficients: $U_\infty=5.6\text{ m/s}, \alpha = 29.4\text{ deg.}$
Figure 14. Lift and drag coefficients: $U_\infty = 10.5$ m/s, $\alpha = 29.4$ deg.

Figure 15. Lift and drag coefficients: $U_\infty = 14$ m/s, $\alpha = 29.4$ deg.