Force Generation Mechanisms by an Insect Wing in Hovering Motion with Different Flipping Schedules

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ABSTRACT

The aerodynamic force and the flow structure of a wing performing hovering motion at small Reynolds number (Re=4000) is calculated by computationally solving the 3D Navier-Stokes equations. The computations are performed for the hovering motion which consists of stroke 1, followed by the flipping motion for reversing the direction and then the stroke 2 (similar to stroke 1 but in the opposite direction). The intent of the study is to research the effects of different scheduling of the flip motion between the two strokes. At Re=4000, the delayed stall mechanism is noted during the azimuth rotation of a wing with a high value of CL due to stabilized Leading Edge Vortex. The lift contribution during the flip (pitch rotation for reversing the direction) for the complete stroke is not substantial. During a stroke, the wing encountered the wake from the previous stroke in which, the wake does not contribute positively.

Keywords: Hovering; Delayed stall; Wake capture; Flip scheduling; Low reynolds number; CFD.

NOMENCLATURE

\( a_\infty \) speed of sound
\( c \) mean chord length
\( C_D \) drag coefficient
\( C_{D_{\text{avg}}} \) time averaged drag coefficient
CFD Computational Fluid Dynamics
\( C_L \) lift coefficient
\( C_{L_{\text{avg}}} \) time averaged lift coefficient
\( l \) radial position along the wing length from axis of rotation
LEV leading Edge Vortex
\( M_\infty \) free stream Mach number
\( \text{Re} \) Reynolds number
\( \text{U}_\infty \) free-stream reference velocity
\( \alpha \) angle of attack
\( \tau \) non-dimensional time
\( \tau_a \) non-dimensional time for acceleration
\( \psi \) azimuth rotation angle
\( \dot{\psi} \) angular velocity of azimuth rotation

1. INTRODUCTION

Flapping flight of natural flyers has always fascinated the researchers and the curiosity has increased manifold due to interest in developing an electromechanical device capable of mimicking the flapping-wing insects. The flapping-wing insects employ unsteady aerodynamic mechanisms to keep them aloft, and there have been many studies on this topic such as Ellington (1984a), Ellington (1984b), Ellington (1984c), Ellington (1984d), Ellington et al. (1996), Van den Berg and Ellington (1997a), Van den Berg and Ellington (1997b), Dickinson et.al (1999), Liu (2002), Liu (2005), Sane (2003), Lehman (2004a), Lehman (2004b) and Wang (2005). During the last few years, computational fluid dynamics (CFD) has also been widely applied to studies concerning insect flight. For instance, Liu and Kawachi (1998), Liu et al. (1998), Sun and Tang (2002a), Sun and Tang (2002b), Wang et al. (2004), Liu (2005), Wu and Sun (2004), Sun and Yu (2006), Yanpeng and Sun (2008), Hamdani and Sun (2000), Yilmaz (2011), Jun-Jiang et al. (2014) and Bross and Rockwell (2014). A major conclusion from these studies is that the insects obtain a sufficient lift force to support their weight through the vortices generated by the flapping wings. Among the many
mechanisms involved in the insect flight, the “delayed stall” identified by Ellington (1996) and Hamdani (2010), which is featured by a prolonged attachment of a leading-edge vortex (LEV) on a wing, has been widely recognized as an important unsteady aerodynamic mechanism contributing to the enhancement of the lift force generation in the flapping-wing insects. Other unsteady mechanisms might contribute to the force production in the insect flight. Dickinson et al. (1999) suggested that the rotational circulation and the wake capture increased the aerodynamic force during the rotational phase of the wing motion. These studies have made significant contributions to the understanding of the different aspects of the aerodynamic mechanisms involved in the insect flight.

Hovering is the condition of staying aloft while having no mean translational motion. It is the most extreme and demanding aspect of the flapping wing flight. The flow over a wing undergoing hovering kinematics is unsteady, such that during one stroke, the wing accelerates and rotates, all the while traveling a distance of only about 3 to 5 chord lengths. Hikaru et al. (2008) performed a CFD study of an unsteady 3D near- and far-field vortex wake dynamics in a hovering fruit fly and their relation to the lift force generation using biologically inspired dynamic flight simulator. By comparing the computed results for the hovering Hawkmoth and the Fruit fly, marked dependence of the span-wise flow and the delayed stall on Re is elucidated.

2. THE PRESENT STUDY

In this work, CFD methodology is applied to understand the instantaneous force generation and vortex structures during hovering motion of a Fruit fly wing. Using the solution of the Navier-Stokes equations, the aerodynamic force and the detailed flow structure around the wing are obtained. The results provide a useful insights into the mechanism of the unsteady force generation during the hovering at Re=4000. The Reynolds number is chosen since this Re range has been used in many studies for MAVs such as by A Naderi et al. (2016). It is pertinent to mention that Re=4000 is selected on the premise that the length scale (mean aerodynamic chord) becomes closer to a Micro Air Vehicle (MAV).

Attention is focused on capturing the unsteady aerodynamic effects during the hovering by systematically scheduling the flip motion between the two strokes. The rationale is to investigate the effects of various flip schedules on the performance of the subsequent stroke with a focus on wake capture mechanism. The experimental study by Dickinson et al. (1999) has used these scheduling to generate force peaks at the start and the end of the stroke leading to wake capture and rotational lift effects. Numerical analysis by Sun et al. (2002a and 2002b) has, as yet, not found any conclusive evidence of wake capture phenomena and has thus, supported the findings of Ellington et al. (1996) that if LEV does not shed, wake capture mechanism might not exist.

3. COMPUTATIONAL METHOD AND GRID GENERATION

3.1 Computational Method

The 3D compressible Navier-Stokes equations are numerically solved in the present study. The Mach number is given a low value such that the solution is a close approximation to that of incompressible flow (further details presented in the next section). For the flow past a body in arbitrary motion, the governing equations can be cast in an inertial frame of reference using a general time-dependent coordinate transformation to account for the motion of the body. Employing this approach, the Navier-Stokes equations are expressed in a strong conservation form. They are well documented in the Beam and Warming (1978) and will not be repeated here.

The Navier-Stokes equations are solved using the implicit, approximate-factorization algorithm of Beam and Warming (1978). The scheme is formulated using the three-point backward implicit time differencing and the second-order finite difference approximation for all the spatial derivatives. A constant coefficient fourth-order explicit and a second-order implicit spectral damping are added to damp the high frequency oscillations and enhance the stability behavior as described by Steger (1978).

The calculations are performed in the still air. At the wing surface, no slip wall boundary condition is enforced which means that the fluid on the wall surface will move with the same velocity as the wall. Along the grid cut-line, the periodic boundary conditions are enforced. The pressure on the boundary is obtained through the normal component of the momentum equation.

3.2 Grid Generation

A body-fitted O-H-type grid is constructed by span-wise stacking the 2-D O-type grids. The two-dimensional grid is generated by using a special Poisson solver based on the methods of Thomas (1982). A portion of the grid used for the wing in span-wise and chord-wise direction is shown in Fig. 1.

For the stacking procedure, the mid span chord is used to normalize the wing under a 7th order polynomial for the leading edge and a 6th order polynomial for the trailing edge. The resulting wing has a span (B) of 2.5 with the aspect ratio (AR= B²/S) 3.74 (Fig. 2).

4. WING KINEMATICS, GRID AND MACH NUMBER SENSITIVITY

4.1 Model Wing Kinematics

Figure 3 depicts the hovering motion, which consists of stroke 1, stroke reversal (flipping) and
the stroke 2. The wing during stroke 1 (translation) performs azimuth rotation around the y-axis. Near the end of stroke 1, the wing decelerates in azimuth rotation in preparation of the stroke 2 which is in opposite direction. Simultaneously the wing performs flipping (pitch rotation) along the spanwise axis for stroke reversal so that angle of attack during Stroke 1 and 2 are same.

For hovering, the flip motion occurs relative to the translation of the wing. A parameter ADF (ADvance Factor) is introduced to relate the scheduling of a flip motion (time) with the azimuth translation during a stroke and it is expressed as:

$$ ADF = \tau_i + \Delta \tau_i - \tau_1 $$

where $\Delta \tau_i$ is the total time for the flipping motion; $\tau_i$ is the instant at which flipping motion (rotation) commences during the stroke and $\tau_1$ is the total time for one stroke, i.e. half cycle ($\tau_i = \tau_d + \Delta \tau_d + \tau_0$), which is set so that the azimuth angle ($\psi$) during a stroke is affixed at 155°. Here, $\tau_0$ and $\tau_d$ are the non-dimensional times during which the acceleration and deceleration in azimuth occurs, respectively and $\Delta \tau_i$ is the non-dimensional time for the constant speed phase of the translation in the azimuth.

ADF (ADvance Factor) essentially provides the value of time at which flipping commences. For instance, ADF= 0.5 implies that half of the flipping motion occurs in Stroke 1 while the other half during Stroke 2 i.e. symmetric flipping. The major parameter for flipping motion is the duration of flipping which is kept constant i.e. $\Delta \tau_i = 1.0$. The translational speed, $v_t$, is equal to $U$ during the constant speed phase. During the acceleration and deceleration phases, $v_t$ is given by:

$$ u_t^* = -0.5 \left[ 1 - \cos \left( \frac{\pi (\tau - \tau_1)}{\tau_o} \right) \right] ; \quad \tau_1 \leq \tau \leq \tau_o \quad (2) $$

$$ u_t^* = 0.5 \left[ 1 + \cos \left( \frac{\pi (\tau - \tau_1)}{\tau_d} \right) \right] ; \quad \tau_2 \leq \tau \leq \tau_d \quad (3) $$

where, $u_t^* = \frac{u_t}{U}$, $\tau = \tau U/c$ (equivalent to number of chord lengths travelled), $c$ is the chord length of the wing and $U$ is a reference velocity. Here Re is also based on $c$ and $U$ and it is 4000. $\tau_1$ and $\tau_2$ are the non-dimensional times at which the acceleration and deceleration start in each stroke, respectively.

Denoting the azimuth rotation speed as $\psi$ ($U=\tau_2 \psi^*$), where, $\tau_2 = \int \frac{\sqrt{\pi} \, dA}{A}$ (second moment of wing area) is calculated as 0.58l, where l is wing span (B) plus the distance between the wing root to the rotational axis (0.25 B). During the pitching motion ($\Delta \tau_i$), the wing pitches from $\alpha_m = \alpha^*$ to $\left(180 - \alpha\right)^\circ$ at an angular velocity whose maximum amplitude ($\alpha_{\text{max}}^*$) is defined by:

$$ \dot{\alpha} = 0.5 \epsilon \left[ 1 - \cos \left( \frac{2\pi (\tau - \tau_1)}{\Delta \tau_i} \right) \right] \tau \leq \tau \leq \tau_o + \Delta \tau_i $$

(4)

where, $\dot{\alpha} = d\alpha/d\tau$, $\alpha_{\text{max}}^*$ is a constant representing the maximum value of $\dot{\alpha}$. During $\Delta \tau_i$, the wing rotates from $\alpha = 40^\circ$ to $\alpha = 140^\circ$; therefore, when either $\alpha_{\text{start}}^*$ or $\Delta \tau_i$ are specified, the other can be determined by the relation $\alpha_{\text{max}}^* = (\alpha_{\text{final}} - \alpha_{\text{start}}) / 0.5 \Delta \tau_i$.

The major parameters in the present study are
Table 1 Description of Cases with different ADFs

<table>
<thead>
<tr>
<th>Case</th>
<th>ADF</th>
<th>( \tau_r ) (Pitching start instant)</th>
<th>Correspondence of Pitching and Stroke 1 Azimuth deceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>4.41</td>
<td>Starts with deceleration</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>4.16</td>
<td>0.25 ( c ) before deceleration commences</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>3.91</td>
<td>0.5 ( c ) before deceleration commences</td>
</tr>
<tr>
<td>4</td>
<td>-0.25</td>
<td>3.66</td>
<td>0.75 ( c ) before deceleration commences</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>4.91</td>
<td>Starts at the end of Stroke 1 deceleration</td>
</tr>
</tbody>
</table>

* ADF = \( \tau_r + \Delta \tau_r - \tau_t \) 
* \( \Delta \tau_r = \tau_a + \tau_d = 0.5 + 0.5 = 1.0 \) 
* \( \tau_t = 4.91 \): time for 1 stroke which includes acceleration, constant speed phase and deceleration 
* During Stroke 1, deceleration starts at \( \tau = 4.41 \)

Table 2 Mean Force Coefficients: Experimental and Numerical Results for a wing in azimuth rotation after rapid acceleration

<table>
<thead>
<tr>
<th>AoA ( \alpha ) (degrees)</th>
<th>Experimental ( \bar{C}_L )</th>
<th>( \bar{C}_D )</th>
<th>Numerical ( \bar{C}_L )</th>
<th>( \bar{C}_D )</th>
<th>% Difference in ( \bar{C}_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1.886</td>
<td>1.55</td>
<td>1.96</td>
<td>1.49</td>
<td>-3.9</td>
</tr>
<tr>
<td>30</td>
<td>1.7128</td>
<td>.938</td>
<td>1.72</td>
<td>.904</td>
<td>-0.11</td>
</tr>
<tr>
<td>20</td>
<td>1.205</td>
<td>.527</td>
<td>1.24</td>
<td>.429</td>
<td>-2.9</td>
</tr>
<tr>
<td>10</td>
<td>.6236</td>
<td>.274</td>
<td>.628</td>
<td>.154</td>
<td>-0.7</td>
</tr>
</tbody>
</table>

\( \bar{C}_L \) data extracted from Fig. 1A [Birch et al. (2004)], error in valves \( \pm 0.25 \)

\( \tau_a = 0.5, \tau_d = 0.5, \Delta \tau_r = 1.0 \) or \( \alpha_0^* = 3.4906 \) at Re = 4000 and \( M_{\infty} = 0.1 \). The motion is continued till approximately the similar mean force coefficients are achieved during the two stroke of a cycle and hence only the final stroke is discussed in the detail. The complete motion’s non dimensional time is normalized to a scale of 1 using the cycle time \( \tau_c \) (which is 9.82).

In essence, there are four variables while considering the motion: Acceleration time \( (\tau_a) \), Deceleration time \( (\tau_d) \), Stroke amplitude \( (\psi) \), and flip velocity \( (\alpha = a c / U) \) and scheduling of the Flipping motion (ADF). In the present study, the following assumptions are made to reduce the number of variables:

(a) Acceleration and deceleration time are kept equal to \( \tau_a = \tau_d = 0.5 \).
(b) Stroke amplitude \( (\psi) \) or azimuth angle during a stroke is fixed at 155\(^\circ\), which corresponds to \( \tau = 4.91 \).

(c) Flipping velocity \( (\alpha = a c / U) \) is given a value such that the wing rotates from \( \alpha = 40^\circ \) to \( \alpha = 140^\circ \) within \( \tau = 1.0 \).

(d) Flipping motion (stroke reversal) is scheduled according to the value of the ADF. A total of 4 cases are considered and the details are presented in Table 2.

4.2 Grid Sensitivity Study

For the Grid independence study, the wing translation starts by accelerating for \( \tau_a \) in the still air (Eq. 1) to a constant speed \( U \) (denoted as Motion 1). Due to this half of the hovering motion (i.e. acceleration and constant speed azimuth rotation only), the grid sensitivity study does not require ADF factor since the stroke reversal (or flip) is not taking place. Mach 0.1 is selected for this study. Two grids are considered: While the Grid 1 is of the size 125 \times 72 \times 76 in the normal, around the wing section, and the span-wise directions, respectively, whereas the Grid 2 is of 156 \times 90 \times 76. The far field boundary is set at 10 chord lengths away from the wing surface in the normal direction and 5 chord lengths away from the tip in the span-wise direction. The calculated lift and drag coefficients are shown in Fig. 4.

It is seen that during the acceleration phase, there is almost no difference between the results of these two grids; however, during constant speed phase,
there is a very small difference between the results, which indicates that results of grid 1 and grid 2 are similar. From the above result, grid 2 is selected for the present study for ensuring more accuracy as well as better resolution of the flow structures.

In the constant speed phase, the lower Mach number gives slightly higher lift coefficient as compared to $M_a=0.1$. Therefore, Mach 0.1 (33 ms$^{-1}$) is selected for the subsequent computations since it would give a good approximation (qualitative) of the incompressible flow at Mach number as low as 0.01 (3.3 ms$^{-1}$).

5. RESULTS AND DISCUSSION

5.1 Code Validation

The code has been validated by comparing the results with the experimental data at the low Reynolds number by Hamdani and Sun (2000). The code validation is also performed by comparing the computational results with the experimental at $Re=120$ and 1400 by Birch et al. (2004), respectively. Table 2 shows the mean lift and drag coefficients at the different angles of attack for the experimental and computational comparison of the results. Figure 6 shows comparative force coefficient plots for the experimental and numerical results. Essentially, the results are similar especially when $a$ is small. Small variation seen in the results could be due to different acceleration time used in the experiment by Birch et al. (2004), which is not known.

5.2 Case 1 (ADF=0.5)

In all the cases, the first cycle commences in the still air with the wing acceleration ($\omega=0.5$) at $\alpha=40^\circ$, which is followed by a constant speed azimuth rotation. During the case 1 at $r=4.41$, the deceleration starts to bring the wing to halt in the azimuth and simultaneously the wings starts to pitch up. At the end of the deceleration, the pitching rate is maximum and $\alpha=90^\circ$. At this stage, the stroke 1 of the cycle ends. Stroke 2 begins with the acceleration in the azimuth and the pitch motion from $\alpha=90^\circ$ to $\alpha=140^\circ$. At the start of the constant speed phase, the pitching is completed and the wing is moving at $\alpha=140^\circ$ through the wake of the Stroke 1. The Stroke 2 deceleration and flipping starts simultaneously and at the end of the deceleration, the Stroke 2 (and Cycle 1) is completed. The wing continues to perform the motion with the same kinematics as the Cycle 1 and the computations are continued till the results of two the successive strokes are similar. Fig. 7 shows the lift and drag coefficients versus $\tau/c$ for the Stroke 4 during the Cycle 2. $\overline{C_L}$ and $\overline{C_D}$ (Weighted average lift and drag coefficients) for the final stroke is 1.35 and 0.79, respectively giving $\overline{C_L}/\overline{C_D}$ of 1.7.

The Stroke 4 starts with a low value of $C_L=0.12$. As $\alpha$ reduces from a maximum value to zero and $\psi$ increases from zero to its maximum value, a peak value of $C_L=1.13$ (Location 1: $\tau/c=1.52$) is achieved. By the end of the acceleration ($\tau/c=1.55$), the $C_L$ peak has subsided. During the constant speed translation phase, the lift coefficient increase is steady till $\tau/c=1.65$. After which, the increase in $C_L$ is gradual and the value of 2.165 (Location 2) is achieved by the end of the constant speed phase. At $\tau/c=1.95$, the azimuth deceleration and the pitch up rotation starts simultaneously, where the $C_L$ drops to -1.128 (Location 3) at about the mid of this phase (or the point of maximum deceleration rate). It then increases to a value of $C_L=0.12$ (at the end of the stroke i.e. the deceleration has finished and $\dot{\psi}$ is maximum).

On the other hand, $C_D$ is 0.63 at the start of the stroke 4 ($\tau/c=1.5$) and increases rapidly during the acceleration in the azimuth direction to a peak value of about $C_D=2.0$ ($\tau/c=1.515$). By the end of the acceleration ($\tau/c=1.55$), $C_D$ peak has also subsided and for the duration of the constant speed
translation phase, the drag coefficient increase is steady and a value of 1.6 is achieved by the end of the constant speed phase. At $\tau/\tau_c = 1.95$, the azimuth deceleration and the pitch up rotation starts simultaneously, as the wing angle of attack increases, $C_D$ increases to a peak of 2.65 ($\tau/\tau_c = 1.988$) and by the end of the deceleration phase, has reached 0.63.

5.3 Case 2 (ADF=0.25)

In Case 2, the kinematics is similar to the Case 1, however the flip motion is initiated 0.25 chord length before the deceleration phase of the stroke 1 and ends at the mid of the acceleration phase of the stroke 2.

The stroke begins with a high negative value of $C_L$ (about -1.5) and $C_D$ is about 1.5. During the starting phase, $\dot{\alpha}$ is decreasing to zero while $\dot{\varphi}$ is increasing. As can be seen from Fig. 8, $C_L$ peak value of 1.865 and $C_D$ peak value 2.05 (location 1) is attained during the acceleration phase. By the end of the acceleration phase, ($\tau/\tau_c=1.55$), $C_L$ drops to less than 1.0. During the constant speed translation, $C_L$ gradually increases (due to delayed stall mechanism) and before the flip starts (0.25 $c$ before deceleration); $C_L$ is approximately 1.97, which is higher than the force peak produced during the acceleration phase. Immediately after the flipping commences, a second peak (location 2) of the force coefficients is observed ($C_L$ and $C_D$ is 2.404 and 3.558 respectively). As soon as the deceleration in azimuth starts, the combined effect of the deceleration and pitching ($\dot{\varphi}$ and $\dot{\alpha}$) is dominated by the deceleration and the lift reduces sharply (between location 2 and 3). At $\alpha=90^\circ$, the lift coefficient is almost zero (location 3). There is then a slight increase in $C_L$ (location 4); however $C_L$...
drops sharply to a high negative value (location 5) by the end of the stroke under the influence of the deceleration.

In comparison with $C_L$, $C_D$ shows a similar behavior with a large peak during the acceleration, which is followed by a drag plateau during the constant speed phase. During the flipping motion, another peak is observed (location 2). A negative peak is seen which corresponds nearly to the maximum deceleration rate and towards the end of the stroke ($\alpha > 90^\circ$), $C_D$ has a positive value due to change in the direction of the drag force. $C_L$ and $C_D$ for the stroke are 1.5 and 1.47, respectively while $C_L/C_D$ is calculated as 1.02.

5.4 Case 3 ($ADF=0.0$)

In the Case 3, the kinematics is similar to the Case 1, however the flip motion is initiated 0.5 chord length before the deceleration phase of the stroke 1 and ends with the deceleration phase of the translation. Or, there is no flipping motion during the acceleration phase of the next stroke.

The stroke begins with $C_L$ about -0.9. During the starting phase, $\omega^*$ is zero (no flipping motion) while $\dot{\varphi}$ is increasing. From Fig. 9, it is seen that qualitatively behavior of the force coefficients is similar to that of the previous case $ADF=0.25$ (Fig. 8). It is seen that the $C_L$ and $C_D$ peaks (location 1: 2.5 and 2.6 respectively) are produced during the acceleration phase. During the constant speed translation, the forces gradually increase and there is a lift and drag plateau during the most part of azimuth translation (delayed stall mechanism). As the flipping motion starts, $C_L$ increase to about 2.7 (location 2) or a lift peak associated with flipping (rotational lift). As $\alpha$ increases further, $C_L$ starts to decrease and at $\alpha=90^\circ$ (which coincides with start of deceleration and maximum flipping rate); $C_L$ is zero. Under the influence of the deceleration, $C_L$ drops to -1 (location 3) and as the maximum deceleration rate is achieved; a positive peak of $C_L = 0.7$ appears (location 4). $C_L$ drops to a negative value of -0.9 at the end of the stroke. It is worthwhile to note that this spike (location 4) is not evident in the previous two cases; thus highlighting the importance of the flipping motion scheduling viz deceleration in the azimuth rotation.

In comparison with $C_L$, $C_D$ shows a similar behavior with the large peak during acceleration, which is followed by a drag plateau during the constant speed phase. During the flipping motion, very high peak is observed corresponding to the maximum flip rate (location 2). During the deceleration, $C_D$ continually decreases and by the end of the stroke, $C_D$ is about -1.25. $C_L$ and $C_D$ for the stroke are 1.51 and 1.7, respectively while $C_L/C_D$ is calculated as 0.88.

5.5 Case 4 ($ADF=-0.25$)

With similar kinematics as the previous cases except that the flip starts 0.75 chords length before the deceleration starts and ends at the mid of the deceleration phase of the stroke ($\alpha=140^\circ$). Therefore, the wing continues to decelerate for the quarter chord length at an angle of attack of 140°.

The stroke begins with $C_L$ and $C_D$ value of -0.4 and 0, respectively. At the start of the stroke, $\omega^*$ is zero (no flipping motion) while $\dot{\varphi}$ is increasing. From Fig. 10, it is seen that qualitatively behavior of the force coefficients is similar to that of the previous case $ADF=0.0$ (Fig. 9). As the wing starts to accelerate, $C_L$ and $C_D$ start to rise till a force peak is achieved (location 1: 2.88 and 2.77 respectively). There is a sudden decrease in $C_L$ and $C_D$ as the acceleration phase ends.

During the constant speed translation phase, the force coefficients stabilize at a high $C_L$ and $C_D$ value as compared to the steady state results thus signifying the stall absence phenomenon. The flipping motion commences 0.75 chords length travel before the azimuthal deceleration. Due to the flipping motion, $C_L$ increases to about 2.66 (location 2) and thereafter it drops sharply. At the mid of the flipping (flipping rate is maximum and $\alpha=90^\circ$), $C_L$ is zero. As the wing continues to rotate beyond 90°, $C_L$ continues to decrease till location 3 due to the orientation of the lift vector. Shortly beyond location 3, the deceleration starts and $C_L$ attains another peak at the maximum deceleration.
rate (location 4; flipping has ended) and similar to the acceleration phase; $C_L$ decreases as the deceleration rate reduces to zero (location 5). It is worthwhile to observe the three positive force peaks (1, 2, 4) and the two negative force peaks (location 3 and 5).

$C_D$, at the start of the stroke is almost zero and increases to a high value during the acceleration. As the acceleration rate reduces, $C_D$ decreases and maintains almost a constant value during the constant speed translation phase. The flipping motion causes the drag coefficient to increase and a very large value ($C_D = 7.8$) is achieved at the instant when the flipping rate is maximum and $\alpha = 90^\circ$ (location 2). Beyond this instant, it then starts to decrease rapidly and is close to zero when the deceleration starts. At the location 4 (the flipping has ended and the deceleration rate is maximum), $C_D$ is about -1.0. Thereafter, $C_D$ increases to a value of zero by the end of the stroke. $\overline{C_L}$ and $\overline{C_D}$ for the stroke are 1.47 and 1.62, respectively and $\overline{C_L}/\overline{C_D}$ is calculated as 0.91.

5.6 Case 5 (ADF= 1.0)

A variation of the Case 1 is also investigated in which the flipping motion occurs during the deceleration of the Stroke 1 and the acceleration of Stroke 2 (the symmetric flip scheduling). The rationale behind investigating this case is on the basis of very good performance during the symmetric flip scheduling and it is worthwhile to reduce the acceleration / deceleration rates during the azimuth (and corresponding the decreased flipping rate) for ascertaining their effect. The kinematics remains the same except for $\tau_\alpha = 1.0, \tau_\theta = 1.0, \Delta \tau = 2.0$ or $\alpha' = 1.745$. The motion is continued till approximately the similar mean force coefficients are achieved during the two strokes of a cycle and hence only the final stroke is discussed in the detail. The complete motion’s non dimensional time is normalized to a scale of 1 using the cycle time $\tau_c$ (which is 10.82).

The Stroke 4 starts with an almost zero value (Fig. 11) and increases during the acceleration in the azimuth to a peak value of $C_L = 0.43$. By the end of the acceleration ($\tau_c / \tau_\alpha = 1.6$), $C_L$ is 1.1, which shows that after subsiding, the lift coefficient has started to rise again. Initially, this rise during the constant speed translation phase is steep and then it gradually increases ($\tau_c / \tau_\alpha = 1.62$ onwards). By the end of the constant speed translation phase ($\tau_c / \tau_\alpha = 1.90$), $C_L$ is 2.08. At $\tau_c / \tau_\alpha = 1.90$, the azimuth deceleration and the flipping starts simultaneously, $C_L$ drops to zero at the mid phase and there is a further decrease till -0.28. It then
increases to a value of \( C_L = 0.0 \) (at the end of the stroke i.e. the deceleration has finished and \( \alpha \) is maximum).

\( C_D \) has a positive value at the start of the stroke \((\tau / \tau_o = 1.5, C_D = 0.115)\) and increases during the acceleration phase to a peak value (location 1) of \( C_D = 0.9 \) \((\tau / \tau_o = 1.53)\) after which it decreases slightly. Thereafter, it begins to increase and by the end of the acceleration \((\tau / \tau_o = 1.6)\), the \( C_D \) is about 1.0. For the duration of the constant speed translation phase, the drag coefficient increase is steady and a value of 1.6 (location 2) is achieved by the end of the constant speed phase. At \( \tau = 1.90 \), the azimuth deceleration and pitch up rotation starts simultaneously. \( C_D \) decreases to a negative peak of -0.765 (location 4). By the end of the deceleration phase, \( C_D \) has a magnitude of 0.1.

It is important to note that due to slow acceleration/deceleration rates, high peaks are not produced (unlike the previous 4 cases). \( C_L \) and \( C_D \) for the stroke are 1.28 and 1.06, respectively, which are lesser than the Case1; \( C_L / C_D \) for the stroke is 1.2.

This case \((\tau_c = 10.82, \Delta \tau_c = 0.185 \tau_c, Re = 4000)\) has the kinematics closer to Sun and Tang (2002a. 2002b), where they used \( \tau_c = 10.82, \alpha = 40^\circ, \Delta \tau_c = 0.185 \tau_c \) and \( Re = 136 \) and calculated a \( \bar{C}_{\tau} = 1.2 \) for one stroke. This is almost similar to the one calculated for the final stroke of the case 2 i.e. \( \bar{C}_{\tau} = 1.19 \).

While in their study on the lift and power requirements for drosophila by Sun and Tang (2002a), \( \bar{C}_{\tau} \) was calculated as 1.15 for a symmetric motion with the wing at \( \alpha = 36.5^\circ \). The results thus, revalidate the initial assumption of the present study that the flow physics at \( M_e = 0.1 \) is essentially similar to \( M_e = 0.01 \) and with these results, the velocity can be estimated to as low as \( U_e = 0.14 \text{ms}^{-1} \) used by Sun and Tang (2002a, 2002b).

### 5.7 Discussion

The complexity of the motion and its accompanying results (the force coefficients) merits discussion on various aspects of all the above cases for the purpose of gaining useful insights.

First, the coefficient of lift behavior during a stroke is discussed:

(a) During acceleration, \( C_\theta \) peak is around 2.0 for all the cases and there is a lag between the force production and the acceleration rate i.e. \( C_D \) peak occurs a little after the maximum acceleration rate.

(b) At the end of the acceleration, \( C_D \) drops and then maintains almost a constant value throughout the constant speed phase.

(c) For the cases where the flipping commences before the deceleration, \( C_D \) increases rapidly to very large positive values. The large value is associated with the flipping and almost coincides with the rotational lift peak (Cases 2, 3 and 4). While in the case 1, the peak is not exhibited since the flipping and deceleration starts simultaneously and under the deceleration effect; the force production due to the flipping is inhibited.

(d) Beyond the location 4 \( (C_D \) peak), \( C_D \) drops sharply under the influence of the decreasing flip rate and more prominently, due to the onset of the deceleration.

From the above discussion, it is seen that the commencement of the flipping before the deceleration gives dividend in the lift production; however the drag penalty is quite large. Table 3 shows the weighted average of the force coefficients during the final stroke. The best aerodynamic efficiency is achieved in the case 1,
where the flipping and deceleration starts at the same time. For the Cases 2, 3 and 4; the prominent lift peaks are exhibited, however the associated drag peak causes overall lesser value of the aerodynamic efficiency. Although the case 5 flip scheduling is similar to the Case 1, however, the drag coefficient is more due to the prolonged motion (the flipping from \( \alpha = 90^\circ \) to \( 140^\circ \)) during the acceleration and from \( \alpha = 140^\circ \) to \( 90^\circ \) during the deceleration takes place in 1 chord length; while in the Case 1, the same occurs in the 0.5 chord length travel) at the high \( \alpha \). It is pertinent to mention that any further increase of the ADF, i.e. more flipping occurring at the start of the new stroke, would lead to drag penalty since the wing would be translating at the high \( \alpha \) (Case 5 exhibits this statement).

For all the cases, it has been computed that the maximum contribution towards the final stroke (occurs in the wake of the previous stroke). Such an analysis is useful for assessing the wake capture phenomena. In Fig. 12, it is seen that the lift force coefficient generated in the 1\(^{st}\) stroke and the final stroke have similar trend with the two interesting observations:

(a) The force coefficient behavior during the acceleration and deceleration phase is quantitatively same.

(b) During the constant speed translation, the lift force coefficients during the final stroke are consistently slightly lower than the first stroke; while the drag coefficient for both the strokes are same.

This implies that the decreased \( C_L \) during the constant speed phase is due to the wake from the previous stroke. Interesting to note is that the negative effect of the wake do not influence the fast acceleration / deceleration phases or in other words, the unsteady effect is dominant. In essence, in the flip scheduling considered in the present study, the wake capture phenomenon to enhance the performance is not observed.

### 5.8 Comparison of First and Final Stroke

For the Case 4, the first stroke (started in still air or in other words pure azimuth rotation) is compared to the final stroke (occurs in the wake of the previous strokes). Such an analysis is useful for assessing the wake capture phenomena. In Fig. 12, it is seen that the lift force coefficient generated in the 1\(^{st}\) stroke and the final stroke have similar trend with the two interesting observations:

- The force coefficient behavior during the acceleration and deceleration phase is quantitatively same.
- During the constant speed translation, the lift force coefficients during the final stroke are consistently slightly lower than the first stroke; while the drag coefficient for both the strokes are same.

This implies that the decreased \( C_L \) during the constant speed phase is due to the wake from the previous stroke. Important to note is that the negative effect of the wake do not influence the fast acceleration / deceleration phases or in other words, the unsteady effect is dominant. In essence, in the flip scheduling considered in the present study, the wake capture phenomenon to enhance the performance is not observed.

### 5.9 Vorticity Plots during Case 1

Figures 13, 14, and 15 show the vorticity plots during a stroke for the case 1 i.e. \( \text{ADF} = 0.5 \). The solid and broken lines represent the positive and negative vorticity lines, respectively. The angle of attack at the beginning of the stroke (\( \tau / \tau_c = 0.5 \)) is 90\(^\circ\). The wing performs a translational acceleration for \( \tau_c = 0.5 \) toward the right while rotating clockwise from \( \alpha = 90^\circ \) to \( 140^\circ \).

Figure 13 shows the vorticity contours at various span-wise locations during the acceleration phase (i.e. from \( \tau / \tau_c = 1.5 \) to 1.55). The wing is surrounded by the vortices from the previous stroke i.e. the deceleration and flipping from 40\(^\circ\) to 90\(^\circ\). Before dilating on the effect of the acceleration on the vortex generation; it is important to partly explain the origin of the vortices from the previous stroke. During the previous stroke, as the wing decelerates, positive and negative vorticity layers are formed on the upper and lower surface of the wing. Simultaneously, the flipping starts which produces new layer of positive vorticity at the upper surface with the existing positive vorticity layer produced during the deceleration. As the wing pitches up, this vortex layer (positive) curls to form the rotation vortex at the leading edge. The positive vorticity at the trailing edge is formed under the negative vorticity layer during the deceleration, which starts to curl form another positive vortex at the trailing edge.

Now as the new Stroke commences, these two positive vortices can be seen detaching as the wing approaches \( \alpha = 90^\circ \), especially at the locations closer to the wing-tip. As the wing rotates beyond \( \alpha = 90^\circ \) (the pitch down and pitching rate decreases), the negative vorticity layers are produced at the upper and lower surface. As the wing accelerates,
At the trailing edge, the negative vorticity generated during the flip combines with the negative vorticity produced during the acceleration and this negative vortex (starting vortex) sheds i.e. moves away from the wing causing a gradual rise of the force coefficients. During the constant speed phase, the flow pictures at two the different instants are quite similar; which explains the force coefficients plateau during the most part of the constant speed phase.

Figure 15 shows the vorticity plots during the deceleration phase. The flipping has also commenced where the wing rotates from 40° to 90°. Due to the deceleration, the negative and positive vorticity layers are formed on the upper and lower surface of the wing under the existing vorticity
Fig. 15. Case 1: Vorticity plots during deceleration phase for stroke 4 at different instants. A, B, and C are the 25%, 50%, and 75% span wise locations.

layers. Simultaneously, the flipping starts which produces the new layer of the negative vorticity at the upper surface with the existing negative vorticity layer produced during the deceleration. The wing continues to rotate till 90° and the cumulative effect of the deceleration and the flipping causes drop in the force coefficients (similar yet opposite to the acceleration phase). The flow pattern continues to be the same during the subsequent strokes.

7. CONCLUSION

One very interesting aspect from the above results is the diversity of the motion combinations which are available at any point in time, leading to enough lift production to keep an insect (at Re 4000) in a sustained flight. The flip scheduling is an important parameter and it has the decisive impact on the aerodynamic efficiency during the hovering motion. For all the cases considered in the study (with the different flip scheduling), the lift plateau is observed due to the delayed stall mechanism attributed to the non-shedding of the LEV. During the fast acceleration and deceleration, the large force peaks are achieved due to the unsteady effect, or in other words, due to the generation of the vortices in a very short period of time. In instances where the flip is scheduled before the deceleration, the rotational lift is produced while the accompanying large drag offsets the advantage in the lift production. In a case where the deceleration and the flip starts simultaneously, the rotational lift is not produced; however the absence of the drag penalty due to the flipping results in the large values of $C_L/C_D$. The wake capture phenomenon is observed but it did not contribute towards the enhancement of the performance, rather the aerodynamic efficiency is reduced during the subsequent stroke.

REFERENCES


