The Functional Significance of Delayed Stall in Insect Flight

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THE FUNCTIONAL SIGNIFICANCE OF DELAYED STALL IN INSECT FLIGHT

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Navier-Stokes simulations over an idealized flapping insect wing reveal a new strategy for vertical force generation in inclined stroke plane hovering: insects use their wing as bluff and streamlined bodies during downstroke and upstroke, respectively. This strategy helps insects to stay aloft. Furthermore, qualitative and quantitative results from our 2-D simulations determine to what extent the delayed stall mechanism is significant for enhanced flight performance in inclined plane hovering.

1. INTRODUCTION

Controlled experiments conducted over the similarly preserved models of hawkmoth [1] and fruitfly [2] have identified an intense attached leading-edge vortex (LEV) over their wings. The presence of delayed stall vortex enhances the circulation and, hence, the aerodynamic lift force generated by the insect. Though unsteady rotational mechanisms are also contributing to the aerodynamic force generation in insects [3], the delayed stall is the most important of all the unsteady mechanisms identified for flapping flight. The delayed stall provides 65% of total weight support to hawkmoth [4, 5], and 88% of total lift force contribution to fruitfly [6]. Attachment of LEV is observed for different animal species (from mayfly to quail) in the Reynolds number (Re) range of 600 to 15,000, and over different biologically relevant wing planforms [7]. Lift enhancement by delayed stall is not unique to insects, but is also utilized by large vertebrates during hovering and slow-flying [8].

Despite the demonstrated importance of delayed stall in many experimental [1–5, 7, 8, 15, 16] and computational [6, 9, 17] studies, and in small insects to large flying animals, the functional significance of delayed stall in hovering insects which oscillate their wings along an inclined stroke plane is still less evident. The distinct feature of such kinematics is that the aerodynamic drag produced on insect’s wings makes a significant contribution to weight support. Numerical simulations of flow over dragonfly wing motion show that 3/4 of total fly’s weight is supported by drag [10]. Given the different strategies of weight support inherent in these horizontal plane and inclined plane wing motions, it is natural to expect that delayed stall, the prominent lift generating mechanism in lift-dependent horizontal stroke plane

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wing motions, may lose its significance in drag-dependent inclined stroke plane wing motions.

In this article, we explain how insects use their tiny wings to exhibit bluff and streamlined body characteristics at different instances of time during the flapping cycle, which helps in weight support. Results from our 2-D simulations provide insights into why circulation-enhancing delayed stall is not highly significant in drag-dependent inclined plane wing motions.

The use of 2-D simulations to understand the flapping wing aerodynamics is justified from the following. The comparison of 3 D Robofly experiments and 2 D numerical simulations results in the following conclusions [11]. Two-dimensional simulations captured major features of the vortex dynamics throughout the stroke cycle; computed drag matches well with the experiments in all cases; and lift agreed with experiments in advanced and symmetrical rotation case. Furthermore, as will be explained in the next section, we make use of dragonfly wing kinematics to understand the fluid dynamics of inclined stroke plane wing motions.

The aspect ratio of dragonfly wing is larger than that of other insect species [12]. When the aspect ratio is higher, the three-dimensional flow effects are not highly significant [13].

2. WING KINEMATICS

Free flight wing kinematics measurements of many insects [14, 15] obtained using high speed video indicated that the wing translational velocity varied
approximately as a simple harmonic function (SHF); however, the insects were filmed with only one camera, so the measurements cannot be considered accurate. Recently, the time course of three-dimensional (3-D) wing motions of freely flying fruitflies [16], honeybees [17], and droneflies [18] were measured using three orthogonally-aligned high-speed cameras. All these studies confirm the variation of translational velocity as SHF and the wing rotation was confined to stroke reversal. Recent tethered flight kinematic measurements of dragonfly [19] confirmed the same prediction for inclined stroke plane kinematics as well. The mathematical approximations to the considered wing kinematics are as follows.

Translational velocity,

\[ v(\tau) = -\sin \left( 2 \frac{c}{A_0} \tau \right) \]  

Angular velocity confined to stroke reversal

\[ \omega(\tau) = \bar{\omega} \left[ 1 - \cos \left( \frac{2\pi(\tau - \tau_r)}{\Delta \tau_r} \right) \right] \quad \tau_r \leq \tau \leq \tau_r + \Delta \tau_r \]  

where \( \tau \) is the nondimensional time, \( c \) is the chord length of the wing, \( A_0 \) is the stroke amplitude, \( \tau_r \) is the time at which the rotation starts, \( \Delta \tau_r \) is the time required to perform the rotation, \( \bar{\omega} = \frac{\Delta \theta}{\Delta \tau_r} \) is the average rotational speed, and \( \Delta \theta \) is the change in angle of attack (AOA) achieved in wing rotation.

The nondimensional period of wing beat cycle (\( \tau_c \)) can be found by the following relation.

\[ 2 \frac{c}{A_0} \tau_c = 2\pi \]  

3. NUMERICAL METHODOLOGY: IMMERSED BOUNDARY METHOD

Understanding the fluid dynamics of flapping locomotion necessitates the simulation of flow over complex moving boundaries. The requirement of generation of a high quality mesh in conventional CFD methods makes it very difficult to handle complex geometries. While simulating the flow past moving boundaries, transient remeshing strategies need to be incorporated to account for the change of shape or orientation of the body in the fluid flow. In addition to an increase in the computational cost, the accuracy and convergence properties of the conventional methods are primarily affected by the quality of the grid.

In order to circumvent the problems associated with conventional CFD methods to handle complex moving boundaries, the governing equations are discretized and solved on a Cartesian mesh. The concept of immersed boundary method (IBM) is made use of to impose the no-slip boundary condition: singular forces of appropriate magnitude and direction are applied at the solid-fluid interface in such a way that this would result in the enforcement of required boundary conditions. These forces are then distributed on the Cartesian grid points to bring in the influence of the presence of the body into the flow field.
Owing to the simplicity with which IBM handles the complex moving boundaries, it has gained the attention of CFD researchers in recent years. Many researchers have used IBM to understand fish hydrodynamics [20–23] and insect aerodynamics [24–27]. The IBM has not only been used to study insect aerodynamics, but also to simulate a range of fluid dynamic problems. Francois and Shyy [28] developed a methodology to simulate multiphase flow and heat transfer, and the same numerical method is used to study the impact dynamics of a liquid drop on a flat surface with heat transfer [29]. A hybrid Cartesian/immersed-boundary method has been utilized to study the natural convection problem in an inclined cavity and a square enclosure with a stationary cylinder [30]. In order to reduce the numerical diffusion near the immersed boundaries, Pan [31] developed an unstructured Cartesian grid solver. Fluid flow and heat transfer characteristics of a two-roll mill have been analyzed using a finite-element immersed-boundary method [32].

Among many variants of existing IBMs, we chose to use the idea of implicit force calculation [33]. Implicit calculation of Lagrangian forces eliminates the time step restriction imposed upon the computation. We make two essential changes. First, time integration of the Navier-Stokes equations has been carried out by means of a second order projection method [34], which provides second order convergence for pressure. Second, we make use of the 4-point regularized delta function [35], which possess much wider stability region and results in efficient enforcement of boundary condition than any other delta functions.

The algorithm for one time step is explained as follows.

1. Solve momentum equations without considering the presence of immersed boundaries and obtain intermediate velocity component \( u^i(x) \). On the domain boundaries, the required boundary conditions for the problem considered are applied.

\[
\frac{u^i - u^n}{\Delta t} = -\frac{3}{2} \nabla_h (uu)^n + \frac{1}{2} \nabla_h (uu)^{n-1} - \nabla_h p^n + \frac{1}{2Re} \nabla_h^2 (u^i + u^n)
\]  

(4)

The convective and diffusive terms are discretized using Adams-Bashforth and Crank-Nicolson schemes, respectively, which provide overall second order accuracy.

2. Obtain the velocity components on the Lagrangian points \( U^i(X_k) \) by interpolating nearby Eulerian points’ velocities \( u^i(x) \).

\[
U^i(X_k) = \sum_x u^i(x) \delta_h(x - X_k) h^2
\]  

(5)

3. Calculate the Lagrangian forces \( F^i(X_k) \) from prescribed boundary velocities \( U^{n+1}(X_k) \) and interpolated velocities at Lagrangian points \( U^i(X_k) \).

\[
\sum_{j=1}^M \left[ \sum_x \delta_h(x - X_j) \delta_h(x - X_k) \Delta s h^2 \right] F^i(X_j) = \frac{U^{n+1}(X_k) - U^i(X_k)}{\Delta t}
\]  

(6)
4. Distribute Lagrangian forces $F(X_k)$ to the nearby Eulerian points $f(x)$.

$$f^*(x) = \sum_{k=1}^{M} F(X_k) \delta_h(x - X_k) \Delta s$$

where $\Delta s$ is the distance between adjacent Lagrangian points.

5. Correct the intermediate velocity $u^s(x)$ using the Eulerian forces $f(x)$ and obtain another intermediate velocity $u^{**}(x)$.

$$\frac{u^{**} - u^s}{\Delta t} = f^*$$

6. Solve a Poisson equation for pressure correction.

$$\nabla_h^2 p' = \frac{\nabla_h \cdot u^{**}}{\Delta t}$$

The algebraic system of equations resulting from discretization of Poisson equation is solved using BiCGSTAB(2) [36].

7. Correct pressure and velocities.

$$p^{n+1} = p^n + p' - \frac{1}{2Re} \nabla_h \cdot u^{**}$$

$$\frac{u^{n+1} - u^{**}}{\Delta t} = -\nabla_h p'$$

For spatial differencing of momentum equations, second order central differencing is used for viscous terms. Since the upwind schemes exhibit excessive artificial diffusion characteristics, convective terms in conservative form are discretized using second order central differencing. First order Euler integration has been applied for time stepping.

In the above formulations, $\delta$ is the Dirac delta function which is employed to transfer the quantities between Eulerian and Lagrangian domains effectively. The two-dimensional discrete version of delta function is.

$$\delta_h(x) = \frac{1}{h^2} \phi(x) \phi(y)$$

where $h$ is the Eulerian mesh width, $x$ and $y$ are the Cartesian components, and $\phi$ is the hat function, which can be formulated in many ways depending upon the number of nearby points it uses. In our solver, we use a 4-point delta function which ensures more accurate boundary condition imposition [35].

$$\phi(r) = \begin{cases} 
\frac{1}{8} (3 - 2|r| + \sqrt{1 + 4|r| - 4r^2}) & \text{if } 0 \leq |r| \leq 1 \\
\frac{1}{8} (5 - 2|r| + \sqrt{-7 + 12|r| - 4r^2}) & \text{if } 1 \leq |r| \leq 2 \\
0 & \text{otherwise}
\end{cases}$$
Aerodynamic forces acting over the immersed boundaries can be evaluated by integrating the Lagrangian forces over the length of the interface, or by integrating the Eulerian forces over the whole fluid domain.

\[ F_V = - \int_{\Omega} f_y \, dx = - \int_0^L F_y \, ds \]  

\[ F_H = - \int_{\Omega} f_x \, dx = - \int_0^L F_x \, ds \]  

where \( F_V \) and \( F_H \) are, respectively, the vertical and horizontal components of the total aerodynamic force, \( L \) is the length of the interface, and \( \Omega \) is the domain which contains the interface. In our study, the forces are nondimensionalized with RMS velocity of flapping and chord length of the wing.

4. GRID DETAILS AND BOUNDARY CONDITIONS

A flat plate of 2% thickness to chord ratio is used to model the wing cross-section. The plate is discretized with 102 Lagrangian points \( \Delta (s = 0.02) \). The size of the rectangular computational domain chosen is \((-30c \leq x \leq 30c, -30c \leq y \leq 30c\)). A small area within the computational domain is discretized with a uniform grid of \( \Delta x = \Delta y = 0.02 \). The size of this area is chosen in such a way that the wing is immersed within the uniform grid region throughout the stroke. A picture of a wing immersed in the nonbody conformal Cartesian grid is shown in Figure 1. When \( A_0/c = 2.5 \), the size of the uniform grid area is \((-1.9c \leq x \leq 0.6c, -2.8c \leq y \leq \)

Figure 1. A close-up view of non-body conformal Cartesian grid over the flat plate.
and is increased when $A_0/c$ increases. In the remaining area of the computational domain, a nonuniform stretched grid is used. The final size of the Eulerian grid in $x$- and $y$-directions for 2.5 chord lengths wing travel is 397 and 438, respectively. The domain and grid independence study are explained in the following subsections.

Since our study is concerned with hovering insects, the wing is moving in still air with the absence of free-stream velocity. Therefore, on the left and right boundaries of the computational domain, the Neumann boundary condition for velocities $(\frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = 0)$ is applied. On the top and bottom boundaries, the symmetry boundary condition $(\frac{\partial u}{\partial x} = v = 0)$ is applied. These are schematically shown in Figure 2. Every flapping cycle is discretized with 2,000 time steps ($\Delta \tau = \tau_c/2000$). All results presented in the subsequent sections are for the wing during the 10th cycle of flapping, by which the forces and the flow reached a periodic state. The instantaneous forces are nondimensionalized with $0.5 v_{rms}^2 c$.

**Domain Independence Study**

The sensitivity of the computational domain size on the numerical computations is evaluated for the $Re=150$ case. The computational domain chosen in our study are domain-1: $(-30c \leq x \leq 30c, -30c \leq y \leq 30c)$ and domain-2: $(-60c \leq x \leq 60c, -60c \leq y \leq 60c)$. It should be noted that the domain-2 is two times that of domain-1 in both directions. In both these domains, the flat plate is represented with 102 Lagrangian points. A small area within the computational domain $(-1.9c \leq x \leq 0.6c, -2.8c \leq y \leq 0.6c)$ is discretized with uniform grid, having $\Delta x = \Delta y = 0.02$. The stretching ratio for the nonuniform grid outside this uniform grid region is maintained the same for both domains.

Figure 4 shows the variation of $C_V$ and $C_H$ for one complete stroke (see Figure 6 for the relation between $C_L$, $C_D$ and $C_V$, $C_H$). Even though the domain-2 is four times that of domain-1, the increase in computational domain results in a negligible amount of change in the force coefficient. Therefore, it can be concluded that the domain-1 is accurate enough to capture the flow field characteristics. For domain-1, in all directions, the outer boundary lays at least 27 chord length away from the wing. The vortices that are formed because of the flapping wings diffuse completely within the domain before they travel 27 chord lengths.
Grid Independence Study

In order to carry out our grid independence study, the optimized size of the computational domain obtained previously viz. \((-30c \leq x \leq 30c, -30c \leq y \leq 30c)\) is considered. The size of the uniform grid region is \((-1.9c \leq x \leq 0.6c, -2.8c \leq y \leq 0.6c)\). In grid-1, the flat plate is discretized with 102 Lagrangian points. The uniform grid region is discretized with \(\Delta x = \Delta y = 0.02\), resulting in the Eulerian grid size of 397 and 438 points, respectively, in \(x\)- and \(y\)-directions. In grid-2, the flat plate is discretized with 204 Lagrangian points. The uniform grid region is discretized with \(\Delta x = \Delta y = 0.01\), resulting in the Eulerian grid size of 605 and 686 points, respectively, in \(x\)- and \(y\)-directions. The stretching ratio outside the domain is the same for both.

![Figure 3. Validation study for inclined stroke plane motion: (a) \(C_H\) comparison and (b) \(C_V\) comparison.](image-url)
grids. Hence, changing the uniform grid region automatically changes the grid size outside the uniform domain accordingly.

The time course of \( C_V \) and \( C_H \) for one complete stroke for different grids is shown in Figure 5. Though the number of Lagrangian points and the number of Eulerian grid points within the uniform grid domain is doubled, the resulting variation in force coefficients is not very significant. During upstroke there is a small variation in computed \( C_H \) for different grids. However, the time history of \( C_V \) almost coincides for both grids considered—the variation is negligible. The stroke-averaged vertical force coefficient, \( \overline{C}_H \) is near zero in our simulations, which confirms that the present kinematics with the chosen variables represent insect

Figure 4. Time history of force coefficients for different computational domain sizes. (a) Vertical force coefficient and (b) horizontal force coefficient.
hovering. Only the variation of vertical force coefficient $C_V$ and the corresponding fluid dynamics of inclined stroke plane hovering is studied in the following sections. Hence, grid-1, 102 Lagrangian points, and $\Delta x = \Delta y = 0.02$ in the uniform grid Eulerian domain is considered accurate for all simulation here.

5. MECHANISM OF VERTICAL FORCE GENERATION

We simulate the flapping wing with the following typical kinematic parameters: Reynolds number, $Re (=v_{max}c/u) = 150$, stroke amplitude, $A_0 = 2.5c$, rotational period is 20% of the period of wing beat cycle ($\Delta \tau_r = 0.2 \tau_r$), and stroke plane angle,
The angle of attack during downstroke and upstroke are 50.6° and 15°, respectively. It has to be kept in mind that the AOA is measured with respect to the stroke plane. All these details are for the dragonfly hovering, similar to the simulations of Wang [10], except that in our study a flat plate is used to model the cross-section of the wing, and the wing rotation in our study is confined to stroke reversal. The necessity of having a lower AOA during upstroke is evident from Figure 6, which shows the relation between lift ($C_L$), drag ($C_D$) coefficients and horizontal ($C_H$), vertical ($C_V$) force coefficients. It can be seen that during downstroke, both lift and drag forces produced on the wings give rise to a large $C_V$; whereas, during upstroke, lift and drag induce a positive and negative $C_V$, respectively. In order to minimize the negative vertical force contribution by drag during upstroke, the AOA is kept small.

Given the very high operating AOA, the wing behaves as if it is a bluff body during downstroke. As shown in Figure 7a, two attached eddies are formed on either side (both leading and trailing edge sides) of the plate which produces very high drag, leading to a large $C_V$. The flow field is analogous to the flow past a bluff body in laminar steady regime. The pressure drag formed over the wing is very high, so that the vertical force production is also high. The net aerodynamic force produced during downstroke is almost perpendicular to the wing (Figure 7a), implying the dominance of pressure forces over viscous forces.

The vorticity field during the mid-upstroke (Figure 7b) reveals that attached shear layers are formed on both surfaces of the wing without any recirculation zone. This is the characteristic feature of flow past streamlined bodies. The aerodynamic force is not perpendicular to the wing but is more inclined to the wing surface, implying that viscous forces are also important in upstroke. It is clear from Figure 7, that the upward component of aerodynamic force produced during the downstroke is much higher than the downward component of aerodynamic force generated during the upstroke. Hence, a positive stroke-averaged vertical force coefficient $\bar{C}_V$ is produced.

\[ \beta = 62.8^\circ \]
The above analysis reveals a remarkable feature of wing kinematics: insects utilize their tiny wing as a bluff body during downstroke, producing enormous pressure drag, and as a streamlined body during upstroke, producing low skin-friction drag. This difference in drag helps insects to hover.

6. DELAYED STALL ANALYSIS

Contribution of Lift

An insect sweeps its wings through the air at an AOA of around 40°–60°. It is known that at such large operating AOA, a fixed wing would stall and initiate von-Karman vortex shedding. In contrast, the flapping wings do not stall. An attached LEV is formed over the wing. The attached LEV integrates its circulation to the wing; in addition to the bound circulation to maintain the Kutta condition at the trailing edge, the circulation induced by LEV enhances the lift forces produced. If the delayed stall mechanism is significant in inclined stroke plane flapping wing motion, the lift forces produced should make more contribution to the weight support. However, we show from the following discussion that such a phenomenon does not occur in inclined stroke plane hovering.

Contribution of drag and lift forces generated on the wings to vertical force is shown in Figure 8. Though the circulation-enhancing LEV is attached to the wing,
the contribution of lift to $C_V$ is much less than that of drag: 83% of total $C_V$ is contributed by drag alone, which is slightly higher than that reported by Wang [10]. The difference may be attributed to the difference in rotation kinematics and wing cross-section between the two studies. Though stall does not occur even at such large AOA during downstroke, we cannot conclude that the delayed stall is significant. In insect flight literature, delayed stall implies the lift enhancement due to the additional circulation by the presence of an attached LEV. Since the drag produced on the wings provide most of the weight supporting force in inclined stroke plane motions, the delayed stall may contribute very little in such wing kinematics.

The contribution of lift and drag to the vertical force during supination is higher than their counterparts during pronation. This difference underscores the importance of wake capture during supination. As has already been stated, the LEV is not formed during upstroke motion. Hence, the wake capture force during the subsequent pronation would be less; whereas, the strong LEV created during downstroke results in a large wake capture force during supination.

**Evolution of Vorticity Field and Force Production**

It has been shown in the previous section that the drag force produced on the wing makes significant contribution to weight support. In this section, we discuss the fluid dynamic basis for this large drag force production. One possibility is that the delayed stall can help in producing the large drag during downstroke: attached LEV not only generates significant lift force but a substantial amount of drag as well. A recent computational study [24] has shown that if the TEV stays attached to the wing, the effectiveness of the delayed stall is reduced. This is because the negative circulation induced by the TEV counteracts the positive circulation induced by the
LEV. Therefore, the lift enhancement by the delayed stall will be highly significant when the size of the positive circulation-inducing LEV is very large, and the negative circulation-inducing TEV is away from the wing.

In order to evaluate the significance of delayed stall, we make concurrent comparison of vorticity field and force production at three time instances during downstroke—the end of pronation (Figure 9a), time at which $C_V$ is maximum (Figure 9b), and the time at which the LEV has fully grown and occupied the whole upper surface and the instance at which TEV has moved away from the wing.

Figure 9. Contours of vorticity and aerodynamic force at different instances of time in the downstroke. (a) End of pronation (corresponding to a’ Figure 8); (b) time at which $C_V$ is maximum (corresponding to b’ Figure 8; and (c) time at which LEV is at its maximum size and TEV has moved away from the wing (corresponding to c’ Figure 8).
From the above discussion, it is clear that the flow field corresponding to Figure 9c is an ideal condition for delayed stall. If the delayed stall is significant, the flow field corresponding to Figure 9c should produce a large vertical force. But the aerodynamic force vector indicates that the net force acting on the wing is very little when compared to other time instances (Figures 9a and 9b). It can be seen from Figure 8, that both the contribution of lift and drag at c' is small when compared to that at a' and b'.

The following two facts are important in explaining the diminished force acting at time corresponding to Figure 9c.

1. The wing is in the decelerating phase of downstroke at that time. When a wing is decelerating, the bound circulation around the wing reduces. Also, the added mass effect deteriorates the aerodynamic performance of the wing during deceleration.
2. When compared to Figures 9a and 9b, the vortices in Figure 9c have moved away from the wing, which results in reduced pressure drag [41]. Hence, the contribution of drag to \( C_V \) is less, as can be seen in Figure 8.

These two effects, i.e., wing deceleration and displaced vortices, work together to produce low aerodynamic force. The contribution of lift and drag to \( C_V \) is maximum when both the LEV and TEV stay attached to the wing (Figure 9b). This flow field is analogous to the bluff body flow in the steady laminar region, and induces a large drag to the wing. Insects rely on this large drag, rather than on delayed stall mechanism, to induce the required vertical force to stay aloft.

**Comparison of Vortex Strength and Force Production**

Both 2-D [24] and 3-D [6] numerical simulations of fruitfly kinematics along the horizontal stroke plane revealed that since the attached LEV was highly diffused in low Re flapping, the lift force production was tremendously reduced. If the delayed stall mechanism imparts a large vertical force in inclined stroke plane flapping, \( C_V \) has to decrease when Re is reduced. In order to check this, we perform a numerical simulation over the same flapping wing kinematics at a small Re value. Figure 10 shows the time course of \( C_V \) for Re of 150 and 10. In contrast to horizontal flapping, as Re is reduced, \( C_V \) is increased in both downstroke and upstroke. While the contribution of lift to \( C_V \) changes little due to the change in Re (Figure 10c), the drag contribution changes drastically (Figure 10b).

It has been shown that the behavior of a wing during downstroke is analogous to that of a bluff body. For flow past bluff bodies in laminar steady regime, when the Re decreases, the base suction pressure is increased due to viscous action [41]. This increase in base pressure gives rise to a large drag coefficient (\( C_D \)) at low Re. In flow past flapping wings, since the von-Karman vortex shedding is not initiated, the above finding can be directly used to interpret our results. During mid-downstroke, the contours of vorticity are shown in Figure 11a. When compared to the plot presented at the same time instance for Re of 150 (Figure 7a), we can see that the vortices are very much diffused and result in increased drag force similar to a bluff body. This drag force, in turn, induces a large vertical force during downstroke.
Figure 10. Comparison of aerodynamic force coefficients at Re 10 and 150. (a) Vertical force coefficient; (b) contribution of lift to $C_V$; and (c) contribution of drag to $C_V$. 
As has already been stated, attached shear layers are formed over the wing without any recirculation zone, which is a characteristic feature of flow past streamlined bodies. The increase in $C_V$ at low Re during upstroke reflects the importance of viscous drag at low AOA wing motion. Low AOA during upstroke manifests itself as the enhanced viscous skin-friction drag. Thin bodies at low AOA experience a larger viscous drag than when they are at high AOA. In addition, the viscous drag would be higher during low Re motion due to the increased influence of viscosity. The increased influence of viscous forces can be seen in Figure 11b. The instantaneous aerodynamic force is more inclined towards the wing surface rather than acting perpendicular to it. This observation, increased $C_V$ in both downstroke and upstroke when Re is reduced, in turn supports the insignificance of delayed stall.

7. CONCLUSION

In summary, we carried out analysis of lift contribution to weight support, concurrent comparison of evolution of vorticity and force production, and influence of vortex strength on vertical force production at different Re. All analyses emphatically point out the fact that insects employing inclined stroke plane motion make less use of delayed stall mechanism. Such insects operate their wing as a bluff body during downstroke, producing enormous pressure drag and as a streamlined body during upstroke, generating low skin-friction drag. This difference in drag helps insects to stay aloft. Additional experiments on 3-D model wings are necessary to confirm this conclusion.

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