IMPLICIT LES SIMULATIONS OF A FLAPPING WING IN FORWARD FLIGHT

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ABSTRACT

Computations of an aspect ratio 3.5 flat plate wing in flapping forward flight are performed. A high-order implicit LES approach is employed to compute the mixed laminar/transitional/turbulent flowfields present for the low Reynolds number flows associated with micro air vehicles. The ILES approach is implemented by exploiting the properties of a well validated, robust, sixth-order Navier-Stokes solver. The analyzed kinematics are a flapping motion described by an anti-clockwise 8 cycle. A Reynolds number based on the freestream velocity of 1250 is prescribed. A detailed description of the dynamic vortex system engendered by the unsteady flapping motion is given and related to the development of lift and thrust during the flapping cycle. Effective angle of attack, which results from the wing motion, and its interplay with the aerodynamic angle of attack play a key role in determining the flow structure and forces produced.

Introduction

Insects present excellent flight performance [1, 2] and are the ideal candidates for bio-inspired flapping unmanned aerial systems. Hovering and forward flight of insects require a high flapping frequency which depends on the insect’s weight. The insect must be able [3] to accelerate the wing in one direction (downstroke), decelerate it and reverse the motion (supination), perform the upstroke, decelerate the wing again and reverse the motion for the next downstroke (pronation). These accelerations and decelerations imply an increase/decrease of the kinetic energy of the wing. An effective design of flapping unmanned aerial systems will try to harness the advantageous biological features required for efficient flight with focus on the maximization of the payload and minimization of the power required to flap the wings. Successful development of these biomimetic flapping unmanned systems will require significant advancements in the fundamental understanding of the unsteady aerodynamics of low Reynolds number fliers. This computational approach has been successfully applied to a variety of problems related to MAV flight [4–9].

Conventional simplified analytical techniques and empirical design methods, although attractive for their efficiency, may have limited applicability for these complicated, multidisciplinary design problems as they do not capture critical flow features. In the present work a high-order implicit LES approach [10] is employed to compute the mixed laminar/transitional/turbulent flowfields present for the low Reynolds number flows associated with micro air vehicles. This ILES approach exploits the properties of a well validated, robust, sixth-order Navier-Stokes solver [11–13].

The focus of this paper will be the simulation and analysis of aeroscience issues associated with an aspect ratio 3.5 wing in forward flapping flight. The particular flapping kinematics chosen are an anti-clockwise 8 flapping cycle first explored by Viswanath and Tafti [14]. An initial investigation of the impact of the structural properties for an equivalent flexible wing was presented by Demasi et al [15]. A detailed analysis of the flow structures generated by the flapping motion and their relation to the forces produced is given.
Wing Description and Kinematics

Forward flight is assumed to take place where a freestream velocity $V_\infty$ (see Figure 1) is assumed constant in magnitude and direction. The stroke plane $\chi$ is assumed to be on a vertical plane perpendicular to the horizontal one, as presented in Figure 1. The flapping motion is described by an anti-clockwise eight flapping cycle. The “O” portions (identified by the second half of the upstroke and the first half of the downstroke or identified by the second half of the downstroke and the first half of the upstroke) of the “8” cycle are perfectly identical. The axes $x_S$ and $y_S$ are on the stroke plane and $z_S$ is perpendicular to it. The axis $y_S$ is also the intersection between the stroke and horizontal planes.

![Figure 1](image1)

**FIGURE 1.** Anti-clockwise 8 flapping cycle: case of vertical plane stroke plane and freestream velocity directed along $z_S$. In this case the $y_S - z_S$ plane is coincident with the horizontal plane.

The wing computed is rectangular and perfectly planar (i.e., no built-in twist or camber are present), Figure 2. It is possible to demonstrate that the aerodynamic angle of attack is influenced by all Euler’s angles $\phi$, $\gamma$, and $\psi$. These angles are useful to move from the wing-attached coordinate system ($x_w$, $y_w$, and $z_w$) to the stroke plane coordinate system ($x_S$, $y_S$, and $z_S$) and vice versa. Figure 3 shows the positive convention. The parameters that need to be prescribed, for a given rectangular wing (see Figures 2 and 3) are the flapping angle $\phi$, the deviation angle $\gamma$, and the pitch angle $\psi$.

![Figure 2](image2)

**FIGURE 2.** Geometry of the rectangular wing.

Kinematic Laws Regulating the Euler Angles

The flapping angle is assigned with the following law:

$$\phi(t) = \frac{\Phi}{2} \cdot \cos \left( \frac{2\pi t}{T} \right)$$

(1)

where the stroke amplitude $\Phi = 60^\circ$. The deviation angle, $\gamma$, is negative over the first half of the downstroke. After the midpoint of the downstroke the deviation angle is positive. At the beginning of the upstroke it is again negative and at the end of the upstroke it is positive. The law chosen to describe this behavior is:

$$\gamma(t) = -\gamma_p \cdot \sin \left( \frac{2\pi t}{T} \right)$$

(2)

where $\gamma = 10^\circ$. The kinematic law adopted for the pitch angle $\psi$ is:

$$\psi(t) = -\psi_p + \psi \cdot \sin \left( \frac{2\pi t}{T} \right)$$

(3)

where $\psi = 32^\circ$, $\psi_p$ is the rotation angle at the pronation phase, and is specified to be $10^\circ$. The kinematic laws are graphically portrayed in Figures 4-6.
Aerodynamic and Effective Angle of Attack

To understand the aerodynamics for the problem being considered it will be helpful to define the concept of the aerodynamic angle of attack and the effective angle of attack. The aerodynamic angle of attack is defined in a plane perpendicular to the stroke plane, Figure 7. The equation for the line on the wing in

\[
x_S = \frac{\cos \gamma \sin \psi}{\cos \psi \cos \phi - \sin \gamma \sin \psi \sin \phi} z_S
- \frac{D \cos \psi \sin \phi + \cos \phi \sin \gamma \sin \psi}{\cos \psi \cos \phi - \sin \gamma \sin \psi \sin \phi} z_S
\]

where \(D\) is the distance to the plane \(\Omega_a\). The aerodynamic angle of attack can be evaluated from the slope of the line as follows:

\[
\tan \alpha_{aero} = \frac{dx_S}{dz_S} = \frac{\cos \gamma \sin \psi}{\cos \psi \cos \phi - \sin \gamma \sin \psi \sin \phi}
\]

To compute the effective angle of attack the velocity of the wing surface must first be calculated from the relation:

\[
V_{flap} = \omega \times r
\]
Using this expression the effective angle of attack may be defined as
\[ \alpha_{\text{eff}} = \alpha_{\text{aero}} - \vartheta \] (9)

where
\[ \tan \vartheta = \frac{-u_{\text{flap}}}{V_{\infty} - w_{\text{flap}}} \] (10)

Aerodynamic Governing Equations
The governing equations solved are the three-dimensional, compressible Navier-Stokes equations. These equations are cast in strong conservative form introducing a general time-dependent curvilinear coordinate transformation \((x, y, z, t) \rightarrow (\xi, \eta, \zeta, \tau)\). In vector notation, and employing non-dimensional variables, the equations are:
\[ \frac{\partial}{\partial \tau} \left( \frac{U}{J} \right) + \frac{\partial F}{\partial \xi} + \frac{\partial G}{\partial \eta} + \frac{\partial H}{\partial \zeta} = \frac{1}{Re} \left[ \frac{\partial F_v}{\partial \xi} + \frac{\partial G_v}{\partial \eta} + \frac{\partial H_v}{\partial \zeta} \right] \] (11)

Here \( U = \{ \rho, \rho u, \rho v, \rho w, \rho E \} \) denotes the solution vector and \( J \) is the transformation Jacobian. The inviscid and viscous fluxes, \( F, G, H, F_v, G_v, H_v \) can be found, for instance, in Reference 16. The system of equations is closed using the perfect gas law \( p = \rho T / \gamma M_a^2 \), Sutherland’s formula for viscosity, and the assumption of a constant Prandtl number, \( Pr = 0.72 \). In the expressions above, \( u, v, w \) are the Cartesian velocity components, \( \rho \) the density, \( p \) the pressure, and \( T \) the temperature. All flow variables have been normalized by their respective freestream values except for pressure which has been nondimensionalized by \( \rho_\infty u_\infty^2 \).

Spatial Discretization
A finite-difference approach is employed to discretize the flow equations. For any scalar quantity, \( \phi \), such as a metric, flux component or flow variable, the spatial derivative \( \phi' \) along a coordinate line in the transformed plane is obtained by solving the tridiagonal system:
\[ \alpha \phi'_{i-1} + \phi'_{i} + \alpha \phi'_{i+1} = b \phi_{i-2} - \phi_{i-1} + a \phi_{i} - \phi_{i+1} \] (12)

where \( \alpha = \frac{1}{3}, a = \frac{14}{9} \) and \( b = \frac{1}{9} \). This choice of coefficients yields at interior points the compact five-point, sixth-order algorithm of Lele [17]. At boundary points 1, 2, \( IL - 1 \) and \( IL \), fourth- and fifth-order one-sided formulas are utilized which retain the tridiagonal form of the interior scheme [11, 18].

Compact-difference discretizations, like other centered schemes, are non-dissipative and are therefore susceptible to numerical instabilities due to the growth of spurious high-frequency modes. These difficulties originate from several sources including mesh non-uniformity, approximate boundary conditions and nonlinear flow features. In order to ensure long-term numerical stability, while retaining the improved accuracy of the spatial compact discretization, a high-order implicit filtering technique [13, 19] is incorporated. If a component of the solution vector is denoted by \( \phi \), filtered values \( \hat{\phi} \) are obtained by solving the tridiagonal system,
\[ \alpha \hat{\phi}_{i-1} + \hat{\phi}_{i} + \alpha \hat{\phi}_{i+1} = \sum_{n=0}^{N} a_n (\phi_{i+n} + \phi_{i-n}) \] (13)

Equation 13 is based on templates proposed in Refs. 17 and 20, and with proper choice of coefficients, provides a \( 2N \)th-order formula on a \( 2N + 1 \) point stencil. The coefficients,
\( a_0, a_1, \ldots, a_N \), derived in terms of the single parameter \( \alpha_f \) using Taylor- and Fourier-series analyses, are given in Ref. 11, along with detailed spectral filter responses. In the present study, an eighth-order filter operator with \( \alpha_f = 0.3 \) is applied at interior points. For near-boundary points, the filtering strategies described in Refs. 13 and 12 are employed. Filtering is applied to the conserved variables, and sequentially in each coordinate direction.

### Time Integration

For wall-bounded viscous flows, the stability constraint of explicit time-marching schemes is too restrictive and the use of an implicit approach becomes necessary. For this purpose, the implicit approximately-factored scheme of Beam and Warming [21] is incorporated and augmented through the use of Newton-implicit, approximately-factored scheme of Beam and Warming. The explicit time-marching schemes is too restrictive and the use of high-order spatial accuracy caused by the second-order implicit operators, artificial dissipation and the diagonal form are eliminated through the use of subiterations. Typically, two to three subiterations are applied per time step.

\[
\begin{align*}
J^{-1p+1} + \phi' \Delta t_s \delta_\xi \left( \frac{\partial \hat{F}}{\partial U} - \frac{1}{Re} \frac{\partial \hat{F}}{\partial U} \right) & \quad J^{p+1} \\
J^{-1p+1} + \phi' \Delta t_s \delta_\eta \left( \frac{\partial \hat{G}}{\partial U} - \frac{1}{Re} \frac{\partial \hat{G}}{\partial U} \right) & \quad J^{p+1} \\
\left[ J^{-1p+1} + \phi' \Delta t_s \delta_\xi \left( \frac{\partial \hat{F}}{\partial U} - \frac{1}{Re} \frac{\partial \hat{F}}{\partial U} \right) \right] \Delta U & = -\phi' \Delta t_s \left[ J^{-1p+1} \left[ (1+\phi)U^p - (1+2\phi)U^n + \phi U^{n-1} \right] 
- U^p \left( \left( \frac{\eta}{\xi} \right) \xi + \left( \frac{\eta}{\xi} \right) \eta + \left( \frac{\eta}{\xi} \right) \xi \right) \right]^{p+1} \\
& + \delta_\xi \left( \hat{F}^p - \frac{1}{Re} \hat{F}^p \right) + \delta_\eta \left( \hat{G}^p - \frac{1}{Re} \hat{G}^p \right) + \delta_\xi \left( \hat{F}^p - \frac{1}{Re} \hat{F}^p \right)
\end{align*}
\]

where

\[
\phi' = \frac{1}{1+\phi}, \quad \Delta U = U^{p+1} - U^p.
\]

For the first subiteration, \( p = 1, U^p = U^n \) and as \( p \to \infty, U^p \to U^{n+1} \). The spatial derivatives in the implicit (left-hand-side) operators are represented using standard second-order centered approximations whereas high-order discretizations are employed for the explicit terms (right-hand side). Although not shown in Eqn. 14, nonlinear artificial dissipation terms [22, 23] are appended to the implicit operator to enhance stability. In addition, for improved efficiency, the approximately-factored scheme is recast in diagonalized form [24]. Any degradation in solution accuracy caused by the second-order implicit operators, artificial dissipation and the diagonal form are eliminated through the use of subiterations. Typically, two to three subiterations are applied per time step.

### Implicit Large Eddy Simulation Methodology

The high-order ILES method to be used in the present computations was first proposed and investigated by Vishal et al [10]. The underlying idea behind the approach is to capture with high accuracy the resolved part of the turbulent scales while providing for a smooth regularization procedure to dissipate energy at the represented but poorly resolved high wave numbers of the mesh. In the present computational procedure the 6th-order compact difference scheme provides the high accuracy while the low-pass spatial filters provide the regularization of the unresolved scales. All this is accomplished with no additional sub-grid scale models as in traditional LES approaches. An attractive feature of this filtering ILES approach is that the governing equations and numerical procedure remain the same in all regions of the flow. In addition, the ILES method requires approximately half the computational resources of a standard dynamic Smagorinsky sub-grid scale LES model. This results in a scheme capable of capturing with high-order accuracy the resolved part of the turbulent scales in an extremely efficient and flexible manner.

### Boundary Conditions

The boundary conditions for the flow domain are prescribed as follows. At the solid surface, the no slip condition is applied, requiring that the fluid velocity at the wing surface match the surface velocity. In addition, the adiabatic wall condition, \( \frac{\partial}{\partial n} = 0 \), and the normal pressure gradient condition \( \frac{\partial}{\partial n} = 0 \) are specified.

The treatment of the farfield boundaries is based on the approach proposed and evaluated previously in Reference 25 for some acoustic benchmark problems. This method exploits the properties of the high-order, low-pass filter in conjunction with a rapidly stretched mesh. As grid spacing increases away from the region of interest, energy not supported by the stretched mesh is reflected in the form of high-frequency modes which are annihilated by the discriminating spatial filter operator. An effective “buffer” zone is therefore created using a few grid points in each coordinate direction to rapidly stretch to the farfield boundary. No further need for the explicit incorporation of complicated boundary conditions or modifications to the governing equations is then required. Freestream conditions are specified at the inflow, side, upper and lower boundaries, while simple extrapolation of all variables is used at the outflow.

When solving the flapping wing problem, the mesh must be allowed to move in accordance with the motion of the wing surface. A simple algebraic method described in Ref. 26 deforms the aerodynamic mesh to accommodate the changing wing surface position.

### Aerodynamic Features of Flapping Flow

Aerodynamic computations have been performed for the previously described rigid wing in isolation undergoing an anti-
clockwise 8 cycle kinematics. The mesh system developed, Figure 8, consists of 249 points in the streamwise direction, 289 points in the spanwise direction and 151 points above and below the wing. 61 points in the chordwise direction and 141 points in the spanwise direction are located on the wing with a maximum spacing of $\Delta y = 0.03$ and $\Delta z = 0.028$. A minimum spacing, $\Delta x = 0.00025$, is specified at the wing surface. The streamwise spacing downstream of the wing was restricted to a maximum of $\Delta y = 0.04$ for 1.85 chord lengths before the mesh was stretched to the downstream boundary. This grid was subdivided into 200 overlapping meshes for parallel processing.

The aerodynamic parameters specified for the flapping wing in forward flight consisted of a Reynolds number based on the freestream velocity of $Re = 1250$. The advance ratio specified is $J = V_\infty/U_{flap} = 0.5$ where $U_{flap} = 2.0\Phi R/T$ where $R$ the distance from the flap axis to the wing tip and $T$ the period of the flapping motion. The Reynolds number based on the flapping velocity is $Re = 2500$. The frequency of the flapping motion correspond to a Strouhal number, $St = 0.2387$ which gives a a period for the motion of 4.19 characteristic times. A time step, $\Delta t = 0.00025$ is employed based on the temporal resolution required for the fine scale flow features observed.

Figure 9 presents the variation of the thrust coefficient, $C_T$, and the lift coefficient, $C_L$, over one period of the flapping motion where time $t^* = 0$ corresponds to the top of the upstroke and $t^* = 0.5$ corresponds to the bottom of the downstroke. Distinct peaks in the two curves are noted at the midpoints of the downstroke and upstroke. An additional peak in the $C_L$ curve is seen near the bottom of the downstroke. The present flapping motion produces thrust over nearly the full flapping cycle whereas positive lift is produced during the upstroke and negative lift is produced during the downstroke. The mean lift generated during the flap cycle is $\bar{C}_L = 1.69$ and the mean thrust is $\bar{C}_T = 1.91$. The labeled circles in Fig. 9 correspond to temporal locations where flow visualizations are presented.

The flow structure during one flapping cycle is shown in Figures 10 (downstroke) and 11 (upstroke). Figures 10a is at the top of the upstroke (pronation). On the upper surface of the wing a small shallow separated vortical flow has formed outboard towards the tip of the wing. A very small tip vortex has also started to form. On the underside of the wing the remnants of the vortical structures previously created during the upstroke and the shed trailing vortex are seen. At this point in the cycle only very low levels of force are produced on the wing. As the wing progresses through the downstroke the remnants of the previous vorticity on the underside of the wing and the shed trailing edge vortex continue to be convected downstream and out of the system. On the upper surface a strong leading edge vortex and tip vortex develop as the downstroke commences. During this initial portion of the downstroke, Figs. 10a-c, these vortices grow in strength and extent but remain pinned at the wing corners. Extensive regions of strong lift and thrust force are produced due to the low pressures that develop underneath these vortices on the upper surface. These forces produce the first peak in the lift and thrust seen in Fig. 9.

As the downstroke continues several interesting new features emerge, Figure 10c-e. A trailing edge and wing root vortex are now clearly seen to have developed. Outboard on the wing the leading edge vortex breaks down and small scale vortical structures are observed in the shear layer that rolls up to form the leading edge vortex. These shear layer vortical structures can be more clearly seen in Figure 12. The origin of these structures is an unsteady interaction of the leading edge vortex with the surface boundary layer. The proximity of the leading edge vortex to the wing surface and the resulting adverse pressure gradient leads to the separation of the surface boundary layer and the formation of a secondary vortical structure (see Figure 12 inset). This structure becomes unstable resulting in an unsteady eruption of vorticity from the wing surface which interacts with the shear layer separating from the leading edge. This unsteady
eruptive process drives the formation of the shear-layer substructures. These shear-layer instabilities have been observed previously in delta-wing flows \cite{27, 28} and for revolving wings \cite{5}. A detailed description of the origin these structures is found in Reference 28.

Figure 13 portrays the breakdown of the leading edge vortex on a combination of two vertical planes through the core of the vortex to capture the curved structure. The intact core of the leading edge vortex is represented by the dark region of high entropy. A rapid decrease in entropy occurs at the point of vortex breakdown. This point also corresponds to the start of a region of reversed axial flow. These are typical characteristics of the onset
FIGURE 11. Flow structure (isosurface of q-criterion colored by pressure coefficient) and force distribution during upstroke portion of flapping cycle. Column 1 shows the flow on the upper surface, Column 2 shows the flow on the lower surface and Column 3 shows the distribution of the lift and thrust force at each time step. f)-j) correspond to the points f)-j) in Fig. 9.

Proceeding towards the bottom of the downstroke the leading edge, wing tip and wing root vortices unpin from the two outboard corners and the trailing edge corner at the root. The vorticity is reoriented forming a ring-like structure that is pinned at the leading edge corner at the wing root. This detached vortex structure moves away from the wing surface and convects downstream with a corresponding reduction in both the lift and thrust forces. By the time the wing reaches the bottom of the downstroke the outboard portion of the vortex has convected further downstream and the inboard sweep of the upstream portion is terminated when the trailing edge is reached with the vortex...
being rapidly turned away from the wing surface, Fig. 11f. A shallow separation region over the outboard portion of the wing and a wing tip vortex also reform at this point. The reformed vortical flow from the leading edge and a region of increased force where the original leading edge vortex departs from the wing surface at the trailing edge results in a brief enhancement of the lift forces, Fig. 11f. This gives rise to the secondary peak in the lift force around $t^* = 0.5$ noted in Figure 9.

As the wing rotates and commences the upstroke portion of the motion the separated flow over the upper surface weakens and the remaining vorticity is shed and convected downstream, Figs. 11 g-h. On the underside of the wing a process similar to that observed on the upper surface for the initial portion of the upstroke is observed with the formation of a leading edge, wake and tip vortex, which are initially pinned at the corners. In the wake of the wing a series of small scale vortices also form, Fig. 11h-i. As the upstroke progresses the tip vortex unpins from the trailing edge corner and connects with the trailing edge vortex. The leading edge vortex breaks down as the upstroke continues, Fig. 11i-j, and also unpins from the leading edge corner and reconnects with the tip vortex resulting in a complex separated flow region covering the outer portion of the wing. At the top of the upstroke the leading edge separation weakens and ultimately the vorticity is shed and convected downstream.

The vortex dynamics and resulting lift and thrust behavior just described can be understood in part by examining the vari-
FIGURE 13. Leading edge vortex breakdown visualized on a plane through the vortex core using contours of entropy and reversed axial flow along the core of the vortex. Cycle time corresponds to Fig. 10e.

FIGURE 14. Temporal variation of the effective angle of attack for various locations along the leading edge.

FIGURE 15. Effective angle of attack at the wing tip, aerodynamic angle of attack, lift and thrust coefficients during one flap cycle.

The effective angle of attack and aerodynamic angle of attack during the flap cycle. Figure 14 displays the effective angle of attack at various locations along the wing leading edge during one flap cycle. During the initial portion of the downstroke a large effective angle of attack develops over most of the wing varying from $\alpha_{\text{eff}} \approx 30^\circ$ at 1/8th span to $\alpha_{\text{eff}} \approx 85^\circ$ at the wing tip. This large effective angle of attack results in the development of the leading edge and tip vortices described earlier, Figures 10 a-c, and the resulting force produced. The reason both lift and thrust occur can be further understood from Figure 15 that compares $\alpha_{\text{eff}}$ and $\alpha_{\text{aero}}$ with the lift and thrust coefficient for one flap cycle. Figure 15 shows that the thrust produced on the downstroke results from the negative aerodynamic angle of attack which tilts the force vector providing a component in the thrust direction. During the second half of the downstroke the effective rapid pitch down motion particularly on the outboard portion of the wing, Figure 14, results in the shedding of the initial vortex developed and the development of a new leading edge vortex, Figures 10d-e. This new leading edge vortex gave rise to the development of the secondary peak in the lift coefficient. Since over this portion of the cycle the aerodynamic angle of attack is small and mostly positive, Figure 15, minimal impact on the thrust coefficient is noted.

During the upstroke the wing attains a positive aerodynamic angle of attack with a larger magnitude than that attained during the downstroke. A negative effective angle of attack develops which combined with the aerodynamic angle of attack again results in the development of a strong vortex system on the underside of the wing and wing thrust due to the force vector tilting. It is interesting to note that at the wing root the effective angle of attack is always positive during the upstroke. This accounts for the lack of a wing root vortex on the underside of the wing during the upstroke. Also the underside leading edge vortex loses
its strength and coherence near the wing root. During the latter stages of the upstroke the positive effective angle progresses continually outboard leading to the loss of the leading edge vortex on the underside of the wing for locations further outboard.

This description of the unsteady vortex dynamics generated by this anti-clockwise 8 cycle is consistent with the features described by Viswanath and Tafti [14] for a similar kinematics albeit for a higher Reynolds number. A number of the vortical features and dynamics noted by Garmann et al [5] for a revolving wing have also been observed for the present case.

Conclusions

Computations for an aspect ratio 3.5 rectangular wing undergoing an anti-clockwise figure 8 flapping motion and forward flight has been presented. The high-order implicit LES scheme employed for the computations exploits a sixth-order compact scheme to capture the resolved part of the turbulent scales. Very high-order low-pass spatial filters provide the regularization of the unresolved small scales. A Reynolds number based on the free stream velocity, \( Re = 1250 \) was specified with an advance ratio, \( J = 0.5 \).

A detailed description of the unsteady vortex development and structure during a complete flapping cycle was presented. The unsteady vortex dynamics generated both lift and thrust as a result of the flapping motion. Large effective angles of attack, which gave rise to strong vortical structures, and force vector tilting provided by the aerodynamic angle of attack allowed for thrust production during both the downstroke and upstroke of the flapping cycle.

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