Research Article

Numerical Investigation on Flapping Aerodynamic Performance of Dragonfly Wings in Crosswind

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Numerical simulations are performed to investigate the influence of crosswind on the aerodynamic characteristics of rigid dragonfly-like flapping wings through the solution of the three-dimensional unsteady Navier-Stokes equations. The aerodynamic forces, the moments, and the flow structures of four dragonfly wings are examined when the sideslip angle \( \theta \) between the crosswind and the flight direction varied from 0° to 90°. The stability of the dragonfly model in crosswind is analyzed. The results show that the sideslip angle \( \theta \) has a little effect on the total time-average lift force but significant influence on the total time-average thrust force, lateral force, and three-direction torques. An increase in the sideslip angle gives rise to a larger total time-average lateral force and yaw moment. These may accelerate the lateral skewing of the dragonfly, and the increased rolling and pitching moments will further aggravate the instability of the dragonfly model. The vorticities and reattached flow on the wings move laterally to one side due to the crosswind, and the pressure on wing surfaces is no longer symmetrical and hence, the balance between the aerodynamic forces of the wings on two sides is broken. The effects of the sideslip angle \( \theta \) on each dragonfly wing are different, e.g., \( \theta \) has a greater effect on the aerodynamic forces of the hind wings than those of the fore wings. When sensing a crosswind, it is optimal to control the two hind wings of the bionic dragonfly-like micro aerial vehicles.

1. Introduction

Flapping-wing micro air vehicle (FMAV) is a novel type of MAV, which integrates lift and thrust in a flapping way. Compared with the traditional fixed wing or rotor aircraft, FMAV is small and has good disguise and maneuverability under a low Reynolds number [1, 2]. FMAV is playing an important role in both military and civilian areas, many studies on the mechanism of flapping flight have been carried out, which has promoted the development of the FMAV greatly [3–8].

Besides the flight aerodynamic mechanism, the flight stability is another obstruction of application for FMAV. Taha et al. [9] analyzed the dynamics and stability of five insects in response to high-frequency, high-amplitude, and periodic wing motion in hovering flight with a second-order averaging technique. Taylor and Thomas [10, 11] firstly studied the dynamic stability of a locust by a modal analysis method in high-speed forward flight. They fixed the locust in the wind tunnel, changed the speed and angles of locust body, and treated the locust as a rigid body with six degrees of freedom. They pointed out that generally, flapping would not result in some instability, even increased the stability relative to gliding flight under the same speed. Ortega-Jimenez et al. [12] examined the effect of the shedding of vortices on the flight stability of hawkmoths in a wind tunnel. Sun and Xiong [13] studied the longitudinal dynamic flight stability of a bumblebee in hovering with the method of computational fluid dynamics under three natural modes: a stable slow subsidence mode, a stable fast subsidence mode, and an unstable oscillatory mode. Liang and Sun [14] analyzed the longitudinal dynamic flight stability of a model dragonfly in
hovering. Traditional fixed wing aircrafts improve the stability by equipping the control surfaces. For FMAV, it is feeble to use control surfaces to provide anti-interference ability because of their small size and light load, and a new way must be found to solve this question. FMAV will unavoidably generate asymmetric aerodynamic forces and moments due to the crosswind or sudden wind in low-altitude flight and even cause instability to crash. Two reasons can explain how birds and insects with a similar size of FMAV are capable of flying steadily under the disturbed condition. One is the wings of birds or insects are flexible [15, 16], changing local shape to adapt the disturbed flow. The other important reason is that birds or insects achieve the stability by changing the flapping parameters of the wings in the complex flight [17].

Most abovementioned studies about FMAV are carried out under stable incoming flow, i.e., the direction of the incoming flow is parallel to the flight direction, and few focuses on the aerodynamic characteristics of FMAV under complex disturbed environment such as crosswind. However, FMAV always encounters the disturbing airflow, and most existing FMAVs have poor anti-jamming capability due to their small inertia. The ability to adapt to the complex flight environment has become one of the major problems for the practicability of FMAV. It is of great interest to examine the flapping aerodynamics of dragonfly wings in crosswind. Therefore, this work analyzes the aerodynamic characteristics including the lateral force and three aerodynamic moments based on a dragonfly model using a numerical computation method in crosswind at low Re. It is expected to provide new ideas and theoretical guidance to the design and control study of FMAV.

2. Lateral Flow and Dragonfly Motion Model

The lateral flow and dragonfly model as shown in Figure 1 are used in the present study. It is assumed that the crosswind blows from the right side of the dragonfly model. The body of the dragonfly model is replaced by a revolution body. Slight changes of wing shape have little influence on aerodynamic force coefficients [18, 19]; thus, the four complex dragonfly wings are simplified based on a real dragonfly. Each wing rotates around its wing root (black dots in Figure 1(a))). A right-hand inertial coordinate system (O-XYZ) is used. The x-axis overlaps the central line of the dragonfly body. Plane XOY is the symmetry plane of the dragonfly model. The angle between the crosswind and the flight direction is marked as $\theta$, which varies from 0° to 90° in the present study. And the crosswind is always parallel to the plane XOZ. LF, LH, RF, and RH denote the left fore wing, left hind wing, right fore wing, and right hind wing, respectively. $U_\infty$ is the speed of the crosswind. $b$ is the wingspan. Slight changes in the thickness of wings have little influence on the aerodynamics [20]; thus, in the present study, a zero-thickness wing model is applied.

As shown in Figure 1(b)), a three-dimensional cylindrical computational domain of $20b \times 20b \times 20b$ is used where the dragonfly model is located at the central position. The whole computational domain is discretized with an unstructured tetrahedral mesh. The velocity at the inlet, the upper, and lower surfaces of the cylinder is set as $U_x = U_\infty \cos \theta, U_y = 0$, and $U_z = U_\infty \cos \theta$. The boundary condition at outflow is set with no velocity gradient. Nonslip wall condition is used on the four wings and the dragonfly model. In order to capture the characteristics of flow field more accurately, the computational domain is divided into three parts: inner, middle, and outer with the grid size increasing from the inner to the outer. Figure 1(c)) shows the initial meshes of the dragonfly model, at this moment, the four wings start to stroke down from the top position.

As shown in Figure 1(d)), the movement of each wing is simplified into two parts: the rotation around its wing axis and the translation in the stroke plane. The rotational axis is 0.25$c$ away from the leading edge, where $c$ is the mean chord length of the fore wing. $\alpha_u$ and $\alpha_d$ denote the angles between the wing and the stroke plane during the upstroke and downstroke, respectively. The rotation happens at the end of the upstroke and downstroke. $\Delta \tau$ denotes the nondimensional time interval over which the flip rotation lasts during the upstroke or downstroke.

Both the fore wings and hind wings translate in the stroke plane, and their kinematic equations are the same. The translation angle of the LH($\phi_L(\tau))$ is given by

$$\phi_L(\tau) = 0.5 \phi_L \cos (2\pi f \tau), \quad (1)$$

where $\tau$ is the nondimensional time, $f$ is the stroke frequency. The rotation angular of the LH($\theta_L(\tau)$) varies with $\phi_L(\tau)$ regularly. The rotation angular velocity of the LH($\theta_L(\tau)^+\theta$) during the whole period is given by

$$\theta_L^{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\dot{\do
where $\theta_L^*$ denotes the mean value of $\theta_L(\tau)^*$. In the rotation time interval $(\Delta \tau = 0.2)$, the LH rotates from $\alpha_d$ to $\alpha_u$; hence, the $\theta_L^*$ can be determined by $\alpha_d$, $\alpha_u$, and $\Delta \tau$. In the present study, the kinematic parameters of flapping wings are used based on the previous study [21], $\alpha_d$ and $\alpha_u$ are equal to $36^\circ$ and $22^\circ$, respectively. The flapping frequency of the four wings $f$ is 40 Hz, and the flapping amplitude $\varphi$ is $30^\circ$. The reference velocity $U_{\text{ref}} = 8b f \varphi/3 = 2.75$ m/s, $\text{Re} = c U_{\text{ref}}/\nu = 1511$, and advance ratio $J = U_{\text{co}}/(4b f \varphi) = 0.15$, $\nu$ is the kinematic viscosity. $\vartheta$ varies from $0^\circ$ to $90^\circ$ with an interval of $15^\circ$.

### 3. Methods and Validation

The flow field of a flapping dragonfly can be a time-dependent 3-D incompressible flow. The Reynolds number of the rigid wings is fixed at 1511, and the fluid field is assumed to be laminar, the governing equations of the flow are unsteady incompressible N-S equations.

\[
\frac{\partial u_i}{\partial x_i} = 0, \tag{3}
\]

\[
\frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2}, \tag{4}
\]

where $u_i$ is the velocity component, $t$ is the flow time, $p$ is the pressure, and $\rho$ is the fluid density.

The instantaneous coefficients of lift ($C_L$), drag ($C_D$), and lateral force ($C_{FZ}$) are given as

\[
\begin{align*}
C_L &= \frac{F_y}{0.5 \rho U_{\text{ref}}^2 S_{\text{ref}}}, \\
C_D &= \frac{F_z}{0.5 \rho U_{\text{ref}}^2 S_{\text{ref}}}, \\
C_{FZ} &= \frac{F_z}{0.5 \rho U_{\text{ref}}^2 S_{\text{ref}}},
\end{align*}
\tag{5}
\]

where $F_x$, $F_y$, and $F_z$ denote the $x$, $y$ and $z$ direction aerodynamic force components, respectively, $S_{\text{ref}}$ is the area of the wings. The time-average coefficients of lift ($\bar{C}_L$), drag ($\bar{C}_D$) and lateral force ($\bar{C}_{FZ}$) are given as

\[
\begin{align*}
\bar{C}_L &= \frac{T_y}{0.5 \rho U_{\text{ref}}^2 S_{\text{ref}}}, \\
\bar{C}_D &= \frac{T_x}{0.5 \rho U_{\text{ref}}^2 S_{\text{ref}}}, \\
\bar{C}_{FZ} &= \frac{T_z}{0.5 \rho U_{\text{ref}}^2 S_{\text{ref}}},
\end{align*}
\tag{6}
\]
where \( F_X \), \( F_Y \), and \( F_Z \) denote the three components of the time-average aerodynamic force.

The point is that the \( x \)-axis points to the tail of the dragonfly model; thus, when \( C_D \) is negative, it means that thrust is generated, i.e., \( C_T = -C_D \) and \( C_L = -C_D \). In order to further analyze the effect of crosswind on the stability of the dragonfly, the three instantaneous moment components and three time-average moment components are calculated as

\[
\begin{align*}
C_{MX} &= \frac{M_X}{(0.5 \rho U_{ref}^2 S_{ref})}, \\
C_{MY} &= \frac{M_Y}{(0.5 \rho U_{ref}^2 S_{ref})}, \\
C_{MZ} &= \frac{M_Z}{(0.5 \rho U_{ref}^2 S_{ref})}, \\
\end{align*}
\]

(7)

\[
\begin{align*}
\bar{C}_{MX} &= \frac{\bar{M}_X}{(0.5 \rho U_{ref}^2 S_{ref})}, \\
\bar{C}_{MY} &= \frac{\bar{M}_Y}{(0.5 \rho U_{ref}^2 S_{ref})}, \\
\bar{C}_{MZ} &= \frac{\bar{M}_Z}{(0.5 \rho U_{ref}^2 S_{ref})}, \\
\end{align*}
\]

(8)

where \( M_x \), \( M_y \), and \( M_z \) denote the \( x \), \( y \), and \( z \) direction instantaneous aerodynamic moment components, respectively, \( \bar{M}_x \), \( \bar{M}_y \), and \( \bar{M}_z \) denote the three components of the time-average aerodynamic moment. Meanwhile, the total aerodynamic forces and moment coefficients are denoted as \( C_{Ltot}, C_{Ttot}, C_{FZtot}, C_{MXtot}, C_{MYtot}, \) and \( C_{MZtot} \).

Since the Reynolds number (\( Re = 1511 \)) is very small, and a laminar model can capture most of characteristics of the flow; thus, a laminar simulation is used in the present study [22]. To simulate the flow around the flapping wings, the CFD solver, Fluent 6.3.26, is used in cases in which the N-S equations are solved based on the finite volume method. The second-order upwind algorithm is employed for space discretization and a first-order implicit algorithm is employed for time discretization. The coupling between the pressure and the velocity is achieved using the SIMPLEC algorithm. The wing motion is incorporated via the dynamic mesh feature using a user-defined function to describe the kinematics. The code for calculating the aerodynamic forces and torques of the four wings is written in C programming language and incorporated into the solver.

To examine the reliability of the numerical methods, a dragonfly model, which was studied by Hu and Deng [23], was employed. The geometric parameters and kinematic parameters of the wings are the same as the experimental setups. Four grids and several time steps per flapping cycle were tested for the experimental case studied by Hu and Deng (2014). Figure 2(a) shows the lift force coefficient variation for four grids (1.4 million, 1.8 million, 2.2 million, and 2.6 million grids) with 100 steps per cycle. It is shown that the results are in good agreement for these four grid schemes. Figure 2(b) shows the lift force for 1.8 million grids with 60, 85, 110, 150, and 200 steps per cycle. There is very little variation apparent in the lift force coefficient when the time step is larger than 110. To ensure the reliability of the results, while increasing the speed of calculation, all subsequent calculations use the 2.2 million grid with 150 time steps per flapping cycle, for which the force results can be considered approximately grid and time step independent. The results of \( C_L \) for the single hind wing and the in-phase fore wing and hind wing are presented in Figure 3 together with

![Figure 2: Grid and time step refinement.](image-url)
the experimental results from Hu and Deng (2014). It is shown that the current results are in a good consistence with the references.

4. Results and Discussion

4.1. Total Aerodynamic Forces and Moments. In present study, we consider six various $\vartheta$ ($\vartheta = 0^\circ$~$90^\circ$, interval of $15^\circ$), and at each $\vartheta$, the aerodynamic forces and moments of the four model wings are calculated. All the aerodynamic forces and moments are given by taking the averaged value from 5 stroke cycles after the flow is fully developed. Figure 2 gives the relationship between $\vartheta$ and the total time-average aerodynamic force and moment coefficients of the dragonfly model. As shown in Figure 4(a), it shows that $\vartheta$ affects $C_{Ltot}$ slightly, and $C_{Ltot}$ decreases slightly and grows slowly when $\vartheta$ varies from $0^\circ$ to $90^\circ$. The change is less than 4%. $\vartheta$ has greater influence on $C_{Ttot}$ and $C_{FZtot}$ relative to $C_{Ttot}$, and $\vartheta$ affects $C_{Ttot}$ most distinctly. $C_{Ttot}$ grows slowly during the change of $\vartheta$ from $30^\circ$ to $60^\circ$. $C_{FZtot}$ increases during the whole change of $\vartheta$. Figure 4(b) shows that $\vartheta$ has an obvious effect on $C_{MXtot}$, $C_{MYtot}$, and $C_{MZtot}$. The numerical magnitude of these three total time-average aerodynamic moments increases while $\vartheta$ grows.

The curves of total time-average aerodynamic forces and moments of the dragonfly model from Figure 4 contain lots of information. When $\vartheta$ is zero, the lift and thrust are generated to support the flight; meanwhile, $C_{FZtot}$, $C_{MXtot}$ and $C_{MYtot}$ are near to zero. In other words, the dragonfly can keep forward flight stability with no lateral displacement.
and velocity. However, $C_{MZ\text{tot}}$ is not zero even at $\theta = 0^\circ$, and it indicates that the forward flight is with pitching and not straight. Experiment of Wang et al. showed the similar results [24]. When $\theta$ increases, $C_{l\text{tot}}$ changes slightly, and the dragonfly fluctuates weakly in the vertical direction. $C_{T\text{tot}}$ increases obviously which is useful for forward flight. But the growing $C_{YZ\text{tot}}$ causes the dragonfly to shift to the lateral direction increasingly, and if the dragonfly does not adjust the flapping parameters timely under this condition, it will deviate the established airline and fail to arrive at the destination. With $\theta$ increasing, $C_{MZ\text{tot}}$ grows leading to violent pitching; meanwhile, $C_{MX\text{tot}}$ and $C_{MY\text{tot}}$ increases which aggravates the instability of the dragonfly and breaks the attitude angles of forward flight. At larger $\theta$, the dragonfly will lose its stability or crash. Hence, the dragonfly needs to adjust its attitude at larger $\theta$ to adapt the crosswind.

4.2. Aerodynamic Forces and Moments of Each Wing. The total time average aerodynamic forces and moments of the dragonfly are decided by the four wings, and controlling the wings means controlling the flight of the dragonfly. Thus, it is necessary to analyze each wing of the dragonfly to provide theoretical references for the design of flapping and control mechanism. Figure 3 shows the relation between $\theta$ and time-average aerodynamic forces and moments of each wing.

Comparing Figures 4 and 5, it states that the forces and moments of each wing are different from the total ones. Figure 5 shows that $\theta$ has a greater effect on the aerodynamic forces than the aerodynamic moments. $C_L$ of LF changes weakly, and $C_l$ of LH increases during the whole $\theta$ as shown in Figure 5(a). However, $C_L$ of RF and RH always decrease and they have similar curves. Figure 5(b) demonstrates that the curves of $C_T$ of the four wings are different from each other, on the whole, the four $C_T$ grow with the increasing $\theta$. Curves of $C_{FZ}$ of LF and LH change slowly closed to horizontal lines, and $C_{FZ}$ of RF and RH increases apparently when $\theta$ changes from $0^\circ$ to $90^\circ$ as displayed in Figure 5(c). Figure 5(d) reveals that $\theta$ has a small effect on $C_{MX}$ of the four wings, and curves of $C_{MX}$ of LH and RH are extremely similar. Figure 5(e) shows that the value of $C_{MY}$ of the four wings increases during the whole $\theta$. Curves of $C_{MZ}$ of the four wings change weakly as shown in Figure 5(f).

Figure 5 makes clear that $\theta$ has various influence on each wing, in other words, the dragonfly cannot fly stably only by adjusting flapping parameters of some wing in crosswind. Strictly speaking, the four wings should be adjusted to realize stable flight; however, it is a great challenge for the flapping mechanism design of FMAV with four wings. Figure 5 indicates that LH and RH obviously affect the lift, thrust, and lateral force, respectively. Overall, $\theta$ has a larger effect on the two hind wings. This result manifests that it can be simplified to control bionic the dragonfly FMAV by changing the flapping parameters of the hind wings in crosswind, which greatly reduces the requirement of flapping mechanism. In the subsequent work, the parameters (such as flapping frequency and flapping amplitude) of hind wings will be investigated deeply to explore how these parameters affect the flight stability quantificationally.

4.3. Instantaneous Aerodynamic Forces and Moments. Figures 6–9 show the coefficients of instantaneous aerodynamic force and moment of the four wings in one flapping cycle at different $\theta$. When $\theta$ increases, the curves of instantaneous aerodynamic force fluctuate greatly, and the curves of aerodynamic moment have a similar result. $\theta$ affects the peak value of the coefficients of instantaneous aerodynamic force and moment, and it is more obvious when $\theta$ is larger. Even though there is no phase difference between fore wings and hind wings, the aerodynamic forces and moments of fore wings are different from those of hind wings because of the interaction between fore wings and hind wings. Figures 6–9 also show that $\theta$ has an obvious effect on the instantaneous lift and small effect on the instantaneous thrust in downstroke and oppositely in upstroke. For the lateral force, $\theta$ affects the left wings in upstroke and right wings in downstroke.

The four wings generate instantaneous lift differently as shown in Figures 6–9, and the curves of $C_L$ are very close during the whole flapping cycle. Only some difference of $C_L$ of LH, RF, and RH occur at $0–0.25$ time as displayed in Figures 7(a), 8(a), and 9(a). It shows that $\theta$ influences the $C_L$ of LH, RF, and RH more obviously than that of LF, which accords with the curves of $C_L$ in Figure 5(a). It should be noted that $C_{MX}$ of LF and LH are clockwise, i.e., $C_{MX}$ are negative, and $C_{MX}$ of RH are anticlockwise. When $\theta$ is zero, the directions of $C_{MX}$ of left wings and right wings are opposite with the same value of $C_{MX}$. It results no $x$-axis moment for the dragonfly, i.e., no rolling happens. However, with the increasing $\theta$, the total $x$-axis moment of left wings and right wings is not zero causing the dragonfly roll, which is negative for forward flight.

Curves of $C_D$ from Figures 6–9 show that the drag of the four wings at different $\theta$ is negative which means thrust. Due to the influence of fore wing, $C_D$ of hind wing wave is larger than that of same-side fore wings. $C_{MY}$ of hind wings have the similar regularity with $C_D$. Compared to the curve of $C_D$ at $\theta = 0^\circ$, with the increasing $\theta$, the difference of the curves of $C_D$ becomes more obvious. At $\theta = 0^\circ$, $C_{MY}$ of left wings and right wings is zero causing no yaw. When $\theta$ grows, $C_{MY}$ of left wings and right wings are not equal; then, the dragonfly rolls seriously. The point is that $y$-axis moment of left wings is clockwise.

Curves of $C_{FZ}$ from Figures 6–9 display that at $\theta = 0^\circ$, $C_{FZ}$ of LF and LH are positive, conversely, $C_{FZ}$ of RH are positive. The total lateral force of left wings and right wings is zero which means the dragonfly has no lateral displacement. When $\theta$ increases, the balance of lateral force of left wings and right wings is broken which causes the dragonfly to move to the lateral side. Meanwhile, the increasing total lateral moment of the four wings makes the dragonfly pitch acute which is also bad for the stable flight.

4.4. Flow Structure. For further analyzing the effect of the crosswind on the aerodynamics, Figure 10 illustrates the vorticity at special times during the whole stroke at $\theta = 0^\circ$.
and $\theta = 60^\circ$. Meanwhile, to explain the mechanism of the crosswind, the pressure distribution of the upper and lower surfaces of the four wings at corresponding times is shown in Figure 11.

When $\theta = 0^\circ$, that is to say, there is no crosswind as shown in Figure 10(a), during downstroke, the contralateral wings of the dragonfly accelerate to stroke from the highest position. The leading-edge vortex (LEV), trailing vortex (TV), and wingtip vortex (WV) are generated on the upper surfaces of the wings. The LEV is spiral and always adheres to the leading edge of the upper surfaces. Thus, a low-pressure area is generated on the upper surfaces causing a pressure difference between the upper surface and the lower
surface to generate the lift (see Figure 11(a)). At 0.25 T, the translation speed reaches the maximum value. Meanwhile, the LEV becomes strongest (see Figure 10(a)), and the first lift peak appears. Near the middle downstroke, the angle of attack is negative which causes a negative drag (see Figures 6–9(b)). Subsequently, the translation speed decreases,
and the LEV starts to shed from the upper surfaces. However, the vortex shedding is delayed due to the quick rotation of the wings, and then, the second lift peak appears. After that, the lift begins to reduce sharply until the end of downstroke (see Figures 6–9(a)). During upstroke, there is always an attached flow around the wings besides the WV.
Figure 8: Coefficients of instantaneous aerodynamic force and moment vs $\theta$. 
Figure 9: Coefficients of instantaneous aerodynamic force and moment vs $\theta$. 
The point is that a high-pressure area is generated on the upper surfaces; likewise, a pressure difference between the upper surface and the lower surface is generated. In this process, the wings stroke almost vertically, thus, a larger drag and a small lift are generated. During the whole stroke, there is no crosswind and the flapping parameters of the contralateral wings are equal absolutely causing the same vortex on both sides of the dragonfly (see Figure 10(a)). The pressure distribution of the upper and lower surfaces of the contralateral fore wings has good symmetry about the symmetry plane of the dragonfly, so does that of the contralateral hind wings (see Figure 11(a)). The aerodynamic forces of the contralateral wings balance and the dragonfly can fly stably.

As \( \vartheta \) increases, the LEV, WV, and AF are still generated which is similar to that at \( \vartheta = 0^\circ \). However, due to the crosswind, the LEV, WV, and AF have a certain degree of lateral deviation (see Figure 10(b))). This deviation changes the pressure distribution of the upper and lower surfaces of the wings resulting to the asymmetric pressure distribution of contralateral wings (see Figure 11(b)). Hence, the asymmetric pressure distribution ultimately leads to the asymmetric aerodynamic forces and torques about the symmetry plane of the dragonfly, when \( \vartheta \) further increases, the asymmetry of vortices and the pressure distribution becomes more obvious. The more obvious asymmetry breaks the balance of the contralateral aerodynamic forces and torques resulting to the dragonfly to lose its stability.

5. Conclusion

This study is aimed at investigating the effect of crosswind on the aerodynamics of a dragonfly. 3-D aerodynamic forces and torques of the four wings are calculated when the angle between the crosswind and the flight direction varies from 0\(^\circ\) to 90\(^\circ\). The flow structure and pressure distribution are displayed to analyze the effect of the crosswind. Results indicate that

1. When \( \vartheta \) varies from 0\(^\circ\) to 90\(^\circ\), \( C_{Ltot} \) changes slightly with the difference of less than 4\%. \( \vartheta \) has a larger effect on \( C_{FZtot} \), \( C_{MXtot} \), \( C_{MYtot} \), and \( C_{MZtot} \) compared to \( C_{Ltot} \).

2. With the increasing \( \vartheta \), \( C_{FZtot} \) and \( C_{MYtot} \) grow, causing the dragonfly to accelerate; meanwhile, the increasing \( C_{Ltot} \) and \( C_{MZtot} \) break the attitude angles of the forward flight which is harmful to the stable flight.

3. The instantaneous aerodynamic forces and moments of the four wings wave more distinctly at larger \( \vartheta \). In downstroke, \( \vartheta \) has obvious influence on instantaneous lift and a small effect on instantaneous thrust, and the results are opposite in upstroke. For the lateral force, \( \vartheta \) affects the left wings in upstroke and affects right wings in downstroke.
(4) $\vartheta$ has a different effect on the aerodynamic forces and moments of each wing of the dragonfly. Compared to the two fore wings, $\vartheta$ has a larger influence on the aerodynamic forces and moments of the two hind wings. Therefore, it can be simplified to control bionic dragonfly FMAVs by controlling the two hind wings in crosswind, which will greatly reduce the difficulty of flapping mechanism design.

Data Availability

The authors are willing to share the data underlying the findings of this work, and the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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