Smart wing rotation and ingenious leading edge vortex control modulate the unconventional forces during insects flights

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Compared with fixed-wing flight, flapping flight can generate a higher lift and is also more maneuverable, largely resulting from the benefits of wing rotation. By analyzing the real wing kinematics of fruit flies, we found that the wing rotation is smart modulated and can be simplified into the advanced $\Phi > 0$, symmetrical $\Phi = 0$, and delayed $\Phi < 0$ modes, where $\Phi$ is the phase between stroke reversal and wing rotation. Thus, an experiment of a Robotic fly at Reynolds number of 240 was designed to address how insects control the flow patterns to modulate the flight forces by the smart wing rotation. Experimental results demonstrated that the flow pattern during a half of stroke is featured by the formation of a spiral LEV, which has a convex shape and connects to the trailing vortex via a tip vortex and a root vortex to form a vortex loop. Through wing rotation, the formation of LEV is enhanced and the pinch-off of LEV can be significantly delayed, resulting in the stabilization of LEV and the generation of unconventional forces. In addition, by modulating the modes of wing rotation, insects obtain distinct wing-vortex patterns including positive, neutral, and negative camber patterns, by which insects control the magnitude and direction of unconventional forces owing to the wake capture mechanism. Therefore, the smart wing rotation not only contributes to the generation of unconventional forces, but also accounts for the control of flow pattern during insects steering maneuvers.

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Natural selection for more than $350 \times 10^6$ years gives insects unsurpassed flight performance and maneuverability. Existing investigations have demonstrated that the generation of unconventional forces is largely owing to wing rotation, and steering maneuvers also depends on the modification in the rotational motion of wing. However, the underlying physical mechanism accounting for how insects modulate the aerodynamic forces by wing rotation is still an open question. To address this question, it is essential to identify how insects control the flow patterns by their wing rotation.

Insects fly by flapping their wings and planes fly with fixed wings. By using the conventional steady-state theory, humans understood the flight of plane but failed to explain the generation of sufficient lift to sustain the flight of insects. As a result, the paradox "insects cannot fly" was given and attracted massive researchers to search for the unsteady mechanisms. The first unsteady mechanism was identified by Weis-Fogh at 1973 and termed the "clap-flying mechanism". Up to now, researchers have identified the general unsteady mechanisms including a stable leading-edge vortex attached on the wing, wake capture, delay stall, rotational circulation, and so on, to explain how insects generate the unconventional forces that is different from the conventional forces explained by the steady-state theory. The interaction between these mechanisms account for the forces generation of many insects including fruit flies, bees, butterflies, and mosquitoes. Most of these unsteady mechanisms are related with the rotational motion of wing, and the higher efficiency of flapping flight rather than steady flight is also largely attributed to the benefits from the wing rotation. Through decades of researches, the knowledges on the unsteady mechanisms accounting for the generation of unconventional forces are well known, although there are still some unresolved questions including the stabilization mechanism of leading-edge vortex, the role of flexibility on aerodynamic forces, and so on. Moreover, accurately predicting the aerodynamic forces during wing rotation is also an remained question, because the evolution of flow pattern during wing rotation is highly unsteady and complex.

Besides the generation of unconventional forces, the unsurpassed aerodynamic performance of insect flight also embodies the remarkable maneuverability. During steering maneuvers, insects remarkably modulate their body and wing kinematics to control the magnitude and direction of aerodynamic forces and torques. By using three-dimensional, high-speed videograph, researchers observed the body motions and wing kinemat-
ics of insects during maneuvers including take-off, hovering, forward flight, fast change in flight speed and/or flight direction, and body saccades[14, 20]. According to the real wing and body kinematics, researchers investigated the aerodynamics forces and torques by using the simple aerodynamic models, the CFD method, or a dynamically scaled robotic model "replaying" the wing kinematics. A detailed review on these investigations was conducted by Sun[2]. These investigations have explained the relationship between the changes of wing kinematics and aerodynamic forces in some degree. For example, insects can change the stroke plane by adjusting the orientation of their body to obtain the horizontal and vertical force components, similarly a helicopter generates thrust by pitching downward. To induce a turn, insects generate differences between the motions of their left and ring wings to obtain torques. By comparing the wing kinematics during different maneuvers, one found that insects steer maneuvers with the minor changes in wing motions and only with surprisingly subtle modifications. By using three-dimensional high-speed video, Fry et al. captured the wing kinematics of free-flying fruit flies as they performed rapid flight maneuvers and then replayed the wing kinematics on a dynamically scaled robotic model[4]. They found that such subtle modifications in wing motion can generate such sufficient forces and torques for steering maneuvers, and the modification of wing rotation plays an significant role in the modulation of aerodynamic forces. However, we are wondering that how to control the wing rotation to modulate the aerodynamic forces and what are the underlying physical mechanisms. Therefore, an experimentally robotic model was designed in this paper to reveal the evolution of flow pattern and address the above questions, because flow pattern determines the aerodynamic forces.

As shown in Fig. 1, the robotic model was immersed in a tank filled with glycerin/water mixture and the digital particle image velocimetry technique was performed to measure the velocity fields in a slice of fluid centered on the wing. Hollow glass beads with a mean diameter of $50\mu m$ and a density of $102 g/m^3$ were chosen as the seeding particles. The particles were illuminated by a 1.5mm thick laser sheet projected by a continuous laser with 10W of power and 532 nm wavelength. When the wing chord is placed perpendicular to the laser sheet, the high-speed camera was triggered to record the images. The time interval between two images was $5000\mu s$ and the recorded region had $2320 \times 1200$ pixels with a spatial field of view of $333 \times 170 mm$. The obtained image were paired and processed by a commercial software software called Fluere, which applies the cross-correlation algorithm described by Scarano and Riethmuller. The interrogation areas were $32 \times 32$ pixels windows with 50% overlap. After the velocity fields were obtained, a second-order accurate scheme was employed to calculate the vorticity fields with the finite differences in velocity data with eight neighboring points.

For many insects, the typical motion of wings is similar with "$\infty$", which consists of wing stroke, wing rotation, and the deviation from the stroke plane. Of particular importance to the aerodynamic forces is the coordinative motion of the wing stroke and rotation. By examining the real wing kinematics during the take-off, forward, and hovering flights of fruit flies, we attempt to identify the differences during insects steering these maneuvers and then "replay" the wing kinematics on the experimental robotic fly. As shown in Fig. 2, the time series of wing kinematics during these maneuvers in two cycles of stroke are presented. According to existing investigations, the time when the wing begins to rotate is a key factor on the manipulations of their wing kinematics. Thus, we carefully examine the phase ($\phi$) between the stroke reversal and wing rotation. When the wing rotation precedes stroke reversal, the advanced mode is performed. When wing rotation occurs symmetrically with respect to stroke reversal, the corresponding mode is symmetrical. The delayed mode is considered when wing rotation is delayed with respect to stroke reversal. For forward flight(Fig. 2(a)), wing rotation and stroke reversal begin at approximately $0.27T$ and $0.32T$, respectively, thereby indicating an advanced mode with $\phi = 5\%T$. For hovering flight (Fig. 2(b)), wing rotation and stroke reversal begin at approximately $0.23T$ and $0.33T$, respectively, thereby indicating an advanced mode with $\phi = 10\%T$. For take-off flight (Fig. 2(c)), wing rotation and stroke reversal begin at approximately $0.28T$ and $0.23T$, respectively, thereby indicating an delayed mode with $\phi = -5\%T$. Accordingly, five sets of experiments including two advanced modes, a symmetrical mode, and two delayed modes, are conducted in our study and the detailed time-dependent wing kinematics are presented in Fig. 2(d).

For the flight of insects, one whole stroke cycle consists of a downstroke phase ($0 < t < 0.5T$) and an upstroke phase ($0.5T < t < 1.0T$). As shown in Fig 3(A), two leading edge vortices (Labelled LEV 1 and LEV2) form on the upper surface of wings during the downstroke and upstroke, respectively. In general, the persistent LEV is a common occurrence in insect flights and accounts for the generation of unconventional forces. In addition, the vorticity sheet separates from the trailing edge of wing and rolls up to form a trailing vortex (TRV), which has the opposite vorticity with LEV. Owing to the pressure difference between the upper and lower surface of wing, a tip vortex (TV) forms at the wingtip region. At the corner area between the root of wing and the body of robotic fly, a root vortex (RV) forms owing to the corner flow. The formation of TV and RV have considerable effects on the formation of LEV. Owing to the revolving motion of wing, including the spanwise transports of vorticity, Coriolis and centrifugal effects, and so on. As a result, LEV has a stereo shape and three-dimensional circulation distribution. As shown in Figs. 3(B)-(D), the circulation of LEVs(LEV1 and LEV2) exhibits a convex distribution and the formation of TV has significantly weaken the strength of LEV near the wingtip. In addition, the shapes of LEVs for the three wing rotation
FIG. 1. Experimental set-up. (A) A robotic fly was immersed in a 1.2m by 1.2m by 2.2m tank filled with glycerin/water mixture (density=1.12 × 10^-3 kg m^-3; kinematic viscosity=115 cSt). The geometry of the tank was designed to minimize potential wall effects. The viscosity of the mixture, the length of the wing, and the flapping frequency of the robotic model were chosen to match the Reynolds number typical of insect flight $Re = 150$. (B) Close-up view of the robotic fly. Two wings were installed with a bee-like body, the motion mechanism was put into the inner of body, and the region of body near the roots of wings was made by rubber. In such situation, the influence of the motion mechanism on the vortices around the flapping wings is minimal. A rotation platform was applied to modulate the time when the laser sheet coincides with the measured section, thus we can collect the time series data at the measured section by using 2D-DPIV. The method has been widely applied. (C) The 200-mm-long model wings were constructed from Plexiglas (3mm thick) cut according to the planiform of a bee. Two coordinate systems are applied. The $x' - y' - z'$ coordinate system is inertial system in lab, the $x - y - z$ coordinate system is a moving system and the origin of this system is at the wing root. $z$ indicates the spanwise direction, and $y$ is the direction perpendicular to the wing plane. In addition, $F_{y'}$ and $F_{z'}$ indicates the lift and drag, respectively.

FIG. 2. Wing kinematics. (A) Wing kinematics of the takeoff flight of fruit fly; (B) Wing kinematics of the forward flight of fruit fly; (C) Wing kinematics of the hovering flight of fruit fly; (D) The designed wing kinematics of the robotic fly in our experiments. The histories of translational velocity for the five experiments are the same and indicated by the red solid line. The dashed lines indicate the angular velocity of wing rotation. Two blue ones indicate the advanced modes with $\phi = 10\% T$ and $\phi = 5\% T$, respectively. The black one indicate symmetrical mode. Two green ones indicate the delayed modes with $\phi = -10\% T$ and $\phi = -5\% T$, respectively. In our experiments, the time of one stroke cycle $T$ is 6s.
modes are nearly identical. During the stroke of flapping wing, the LEV remains stable attached on the wing and significantly interacts with the wing during the wing rotation, as shown in Fig. 3(A).

As a consistent feature in the wake of biological propulsion, vortex loops provide an alternative perspective to understand the wake pattern of flapping wing. As shown in Fig.3(E), a vortex loop model, which consists of the LEV connected to the TRV via a TV and a RV, is suggested. During one whole cycle of stroke, two distinct vortex loops form and generate interactive mechanism to enhance the fluid forces. Moreover, insects also obtain the unconventional forces by using an "wake capture" mechanism, in which wing benefits from the shed vortex loop of the previous stroke.

In the vortex loop, of particular importance to aerodynamic forces is the presence of a stable LEV, whose formation explains the sustainable increase of lift at high angle of attack and an instantaneous peak of lift at the beginning of wing rotation(shown in the results of [3]). By contrast, the formation of TV and TRV mainly contributes to the drag-generation. Thus, we attempt to focus on the formation of LEVs and address how to control the formation of LEVs by wing rotation.

To track the formation of LEV, we calculate the circulation at each spanwise cross section by using Stokes’ theorem:

$$\Gamma = \int \int_A \omega_z \, dA,$$

where the area A was determined in each time step to encompass the vortex of interest. In Fig 4, the formation of the LEV1 and LEV2 is shown for advanced, symmetrical, and delayed modes of wing rotation. According to Joukowsky’s theorem and vorticity-moment theorem, the lift-generation strongly depends on the LEV circulation. As shown in Fig. 4, the maximum circulation of LEV1 and LEV2 for advanced mode is larger than these for symmetrical and delayed modes. In addition, the maximum circulation of LEV1 is found to occur at $t/T \approx 0.44$ for advanced mode, whereas it occurs at $t/T \approx 0.25$ and $t/T \approx 0.2$ for symmetrical and delayed modes, respectively. This result indicates that the separation of LEV1 for advanced mode is much later than these for symmetrical and delayed modes. Moreover, this result also suggests that the lift can be further enlarged for advanced mode owing to the continuous growth and delayed separation. As shown in Fig.4, the circulation of LEV1 at the cross sections of $z/R > 0.85$ begins to decrease at a earlier time than these at the other cross sections, which is owing to the formation of tip vortex (TV). When TV is formed of enough strength, TV can weaken the formation of LEV. In all cases, the formation of LEV2 formed in upstroke has the identical process with the formation of LEV1. It should be noted that the strength of LEV2 is smaller than that of LEV1, because the angle of attack in downstroke is smaller than that in upstroke.

When examining the mechanism of LEV formation and separation, the idea of vortex formation time, originally developed for vortex ring formation and proposed by Gharib et al., provides an alternative and physical perspective, which has been widely extended to investigate many canonical vortices including the tip vortex, two-dimensional LEVs, and Kármán vortex. It is found that of particular importance is the common occurrence of vortex pinch-off, which causes the limiting formation of vortex. Based on vortex formation time, a universal timescale ($T \approx 4.0$) is found and coincides with the occurrence of vortex pinch-off. This universal timescale is named "formation number" or "pinch-off time". The finding of formation number actually implies a unifying principle of optimal vortex formation in biological propulsion. Once vortex pinch-off occurs, the vortex reaches its maximum circulation and separates from its generator. Thus, we infer that the LEVs in flapping wing remains stably attached the wing before they pinch off, and LEVs shed into the wake after they pinch off. Moreover, we are wondering whether the formation number of LEVs can be modulated by controlling the kinematics of flapping wing.

In general, the vortex formation time has two definitions. One is the physical definition based on the circulation production mechanism of vortex, and the other one is the dynamic formation time based on the kinematics of vortex generator. The definition of physical formation time ($T^*$) was proposed by Dabiri and shown as

$$T^* = \frac{\Gamma}{D \Delta U}, \quad \Gamma = \frac{1}{2} (2\pi f s)$$

where, $\Gamma$ is the circulation of vortex, $D$ is the characteristic length scale, and $f$ is the flapping frequency.

The dynamic formation time was originally defined by Gharib and also extended to analyze the formation of two-dimensional LEV. Its definition is presented as

$$F^* = \int_0^T u(t) + \frac{1}{2} \omega(t) \sin(\theta(t)) \, dt + \frac{\Gamma}{D \Delta U}$$

where, $u(t)$ is the translational velocity, $\omega(t)$ is the angular velocity of wing rotation, and $\theta(t)$ is the attack angle. In common, the dynamic formation time can be derived from the physical formation time, such as the axisymmetric vortex rings generated by a piston-cylinder apparatus.

Considering the convex shape of LEVs and their spanwise circulation distribution, the modified definition of the physical formation time is given by

$$T^*_{LEV} = \frac{\int_0^L T^* \, cdz}{S},$$

and the modified definition of the dynamic formation time is given by

$$F^*_{LEV} = \frac{\int_0^L F^* \, cdz}{S} + \frac{\Gamma(0)}{D \Delta U},$$

where, $\Gamma(0)$ is the initial circulation of LEV at the beginning of downstroke or upstroke. For all the cases, the
FIG. 3. Flow pattern in flapping flight. (A) Flow visualization during the stroke four. The vorticity contour and flow vectors at three spanwise positions are demonstrated. ((B)-(D)) The spanwise distribution of LEV circulation for advanced mode (B), symmetric mode (C), and delayed mode (D). The solid and dotted lines denote the LEVs during downstroke and upstroke, respectively. (E) A vortex loop model is suggested to describe the flow patterns around the flapping wing.

physical formation time and dynamic formation time of LEVs are calculated based on the experimental results and the commanded wing kinematics, respectively. In Figs. 5(A)-(C), we show the development of $T^*_{LEV}$ and $F^*_{LEV}$ of LEVs for the advanced, symmetrical, and delayed modes. It is found that $T_{LEV}$ of LEVs in the three modes reaches the maximum value at a certain time. By contrast, $F^*_{LEV}$ continues to increase until the wing reverses stroking at $t/T = 0.5$ and $t/T = 1.0$, because the calculation of $F^*_{LEV}$ depends on the kinematics of flapping wing. Before $T^*_{LEV}$ reaches the maximum value, the variation of $T^*_{LEV}$ agrees with that of $F^*_{LEV}$, as shown in Figs. 5(A)-(C). When examining the maximum value of $T^*_{LEV}$, known as the formation number $\hat{T}$, the $\hat{T}$ of LEV is found to be approximately 7.5, 5.5, and 5.0 for $\Phi = 10\%T$, $\Phi = 0T$, and $\Phi = -10\%T$, respectively. This finding implies that the formation number of LEVs can be varied by the rotational motion of wing. However, one question arises that why the wing rotation can vary the formation number of LEVs. In the investigations on vortex rings, Gharib and his cooperators found that the formation number of vortex rings varies by some parameters including the velocity of piston, the presence of uniform background flow, and the temporarily variation of exit diameter. Particularly, the formation number of vortex rings can increase up to 8.0, when a temporally decreasing nozzle exit diameter is introduced. By re-examining the relationship between the motion of flapping wing and the definition of vortex formation time, one may find that the rotational motion has the identical roles on modulating the characterize length scale and varying the supplying velocity. Thus, the formation number of LEVs should depend on the rotational motion of wing. Fig. 5(D) shows the variation of formation number of LEVs for the five cases with different wing rotations. When the wing rotation changes from delay mode to advanced mode, the formation number of LEVs increases from approximately 5.0 to 7.5. In contrast, the formation number of 2D LEV is much smaller and stays in the range of 4.0-5.0, which is obtained by Rival et al. In terms of the formation number of 3D LEV, an alternative mechanism accounting for its stabilization is owing to the delayed pinch-off of LEV. As is known, the larger formation number of vortex means that vortex separates at a later time and a larger force is generated. Thus, insects can appropriately control the formation of LEV and the corresponding fluid forces by smart wing rotation, according to flight demand.

During the wing rotation, the wing passes through the shed vortex from the previous stroke and captures the energy from it if correctly orientated. This mechanism is termed as "wake capture", in which the wing obtains unconventional forces and saves energy. Based on the quasi-steady theory and experimental measurements, one
found that the unconventional forces are sufficient to rotate the wing passively without addition aid. However, modulating the phase \( \Phi \) by only passive wing rotation is difficult. When steering maneuvers, the subtle modifications in wing rotation should be actively behaviours and induces the changes in flow pattern around the flapping wing. In Fig. 6, the flow patterns are shown for the advanced, symmetrical, and delayed modes of wing rotation by diagrammatic cartoons on the basis of the experimental results, whose details are presented in the attached accessories. In Fig. 6, the cross section of vortex loop mainly consisted of LEV and TRV is shown. If the wing rotation precedes stroke reversal, the vortex loop generated by the previous stroke is completely placed under the wing so as to generate a large force. In contrast, with delayed or symmetrical rotation, only one part of the vortex loop is captured, so as to generate a smaller force. Moreover, the motion of wing also aims to alter/arrange the propagating direction of the previous vortex loop (LEV0 and TVR0) to modulate the direction of the unconventional forces. For advanced mode of wing rotation, the wing is arranged with positive camber at the start of stroke, corresponding to a positive-lift pattern. If the wing rotation is symmetrical or delayed with stroke reversal, the wing is arranged with neutral or negative camber, resulting in zero-lift and negative-lift pattern. Collectively, the combined effect of LEV formation and flow pattern.

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FIG. 6. Diagram of the flow patterns. The line represents the wing chord, with the circle indicating the leading edge. Warm tones (reds) represent counter-clockwise vorticity; cool tones (blues) represent clockwise vorticity. The depth of color reflects the strength of vortices. The arrows on the line and in the bottom of each subfigure indicate the moving and rotational direction of wing, respectively.

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