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Flapping Wings and Aerodynamic Lift: The Role of Leading-Edge Vortices

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AT THIS time, there is a controversy concerning the role of the leading-edge vortex (LEV) in enhancing aerodynamic lift during flapping flight. The LEV is generated from the balance between the pressure gradient, the centrifugal force, and the Coriolis force in the momentum equation. The LEV generates a lower pressure area, which results in a large suction on the upper surface. Employing three-dimensional Navier–Stokes computations, we show that the LEV is common to the flapping wing aerodynamics at Reynolds number (Re, based on characteristic chord and flapping speed) of $\mathcal{O}(10^4)$ or lower, which corresponds to the insect flight regime. However, the LEV's main characteristics and the implications on lift generation change as the Reynolds number (wing sizing, flapping frequency) varies.

Figure 1 shows the streamline patterns at three Reynolds numbers; Fig. 1a corresponds to a hawkmoth hovering at $Re = 6000$, Fig. 1b corresponds to a fruit fly at $Re = 120$, and Fig. 1c corresponds to a thrips at $Re = 10$. At $Re = 6000$, an intense, conical leading-edge vortex core is observed on the paired wings with a substantial spanwise flow at the vortex core, breaking down at approximately three-quarters of the span toward the tip. At $Re = 120$ (Fig. 1b), the vortex no longer breaks down and is connected to the tip vortex. The spanwise flow at the vortex core becomes weaker as the Reynolds number is lowered. Further reducing the Reynolds number to $Re = 10$, a vortex ring connecting the leading-edge vortex, the tip vortex, and the trailing vortex is observed (Fig. 1c); the flow structure shows more of a cylindrical than a conical form. Inspecting the momentum equation, one can see that the pressure gradient, the centrifugal force, and the Coriolis force together are likely to be responsible for the leading-edge vortex stability.

Ellington et al. [1] investigated the aerodynamics of hawkmoths and first suggested that the LEV can significantly promote lift associated with a flapping wing. There have been multiple follow-up investigations (e.g., [2–6]) based on different insect models, resulting in varied views on the role played by the LEV and implications on lift generation. For a Reynolds number around $\mathcal{O}$ (10^3–10^4), corresponding to larger insects such as hawkmoths, the LEV can enhance lift by attaching a bounded vortex core to the upper leading edge during wing translation. To be effective in enhancing lift, the LEV needs to maintain a high axial flow velocity in the core and remains stable along the spanwise direction, before separating from the wing at, say, 75% of the spanwise location toward the wing tip, and then connecting to a tip vortex. The overall vortical structures are qualitatively similar to those of low aspect-ratio delta wings [1,2] which stabilize the LEV due to the spanwise pressure gradient, increasing lift well above the critical angle of attack. In essence, the vortex stability in flapping wings is maintained by a spanwise axial flow along the vortex core, creating "delayed stall," to enhance lift during the translational phase.

Birch and Dickinson [5] investigated the LEV related to the fruit fly at the Reynolds number of 160. They report that, in contrast to the hawkmoth LEV, the LEV of the fruit fly exhibits a stable vortex structure without separation during most of the translational phases. Furthermore, there is little axial flow in the vortex core, amounting to only 2–5% of the averaged tip velocity. Observing the considerable difference exhibited between fruit fly and hawkmoth models, Birch and Dickinson [5] hypothesized that the attenuating effect of the downwash induced by the tip vortex and wake vorticity limits the growth of the LEV by lowering the effective angle of attack and prolongs the attachment of the LEV. Our studies show that the downwash can lower the lift production approximately by 17% at the hawkmoth's hovering Reynolds number, and by 22% at the fruit fly's hovering Reynolds number; the difference seems less than substantial.

Examining the facts from the established unsteady aerodynamic viewpoint, the LEV as a lift enhancement mechanism may be questionable because a dynamic-stall vortex on an airfoil is often found to break away and convects elsewhere as soon as the wing translates [7]. The literature on the helicopter blade models have been used to help explain the flapping wing aerodynamics; however, spanwise axial flows are generally considered to play a minor role in influencing the helicopter aerodynamics [8,9]. In particular, the helicopter blades operate at substantially higher Reynolds number

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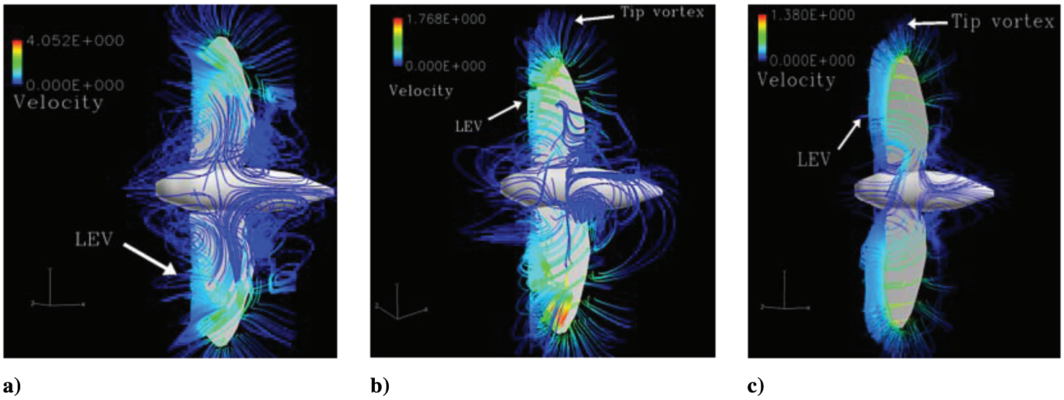

Fig. 1 Numerical results of leading-edge vortex structures at different Reynolds numbers.

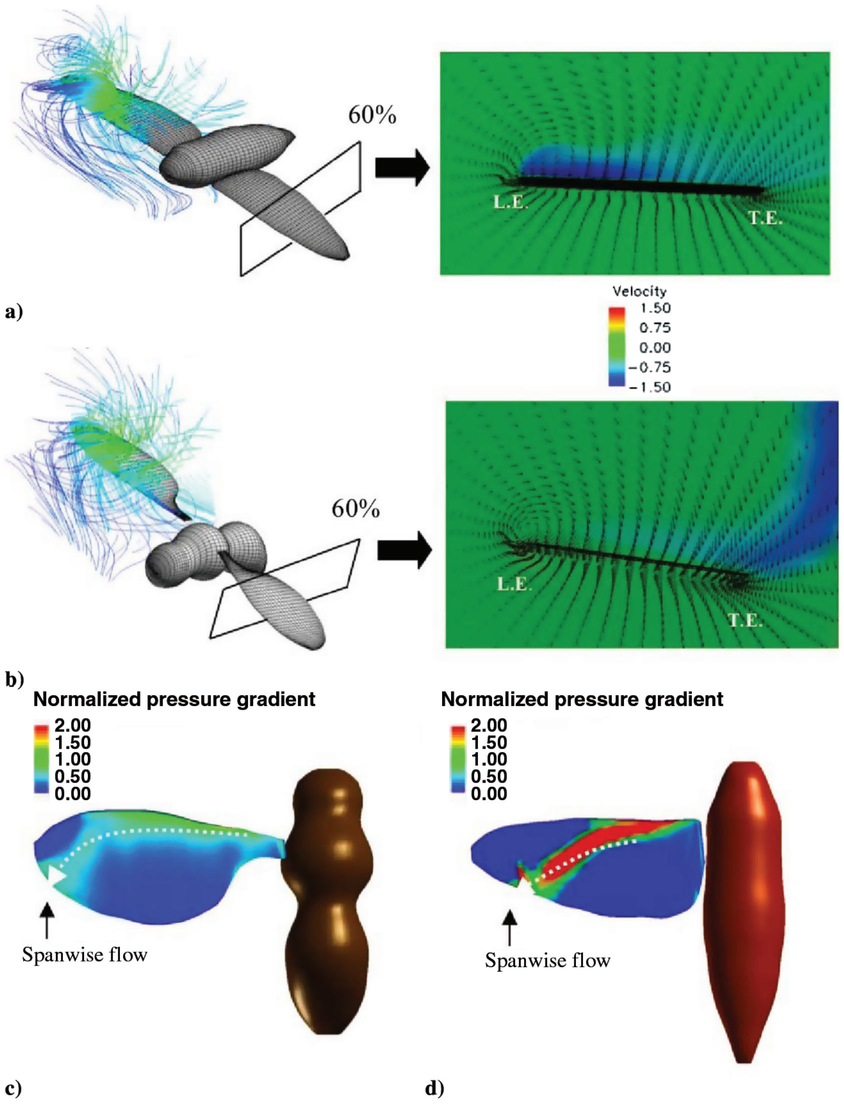

Fig. 2 Comparison of near-field flowfields between a fruit fly and a hawkmoth. Wing-body computational model of a) a hawkmoth ($Re = 6000$), and b) a fruit fly model ($Re = 134$), with the LEVs visualized by instantaneous streamlines and the corresponding velocity vectors in a plane cutting through the left wing at 60% of the wing length; pressure gradient contours on the wing surface for c) a fruit fly and d) a hawkmoth. The pressure gradient indicates the direction of the spanwise flow.

and lower angle of attack. The much larger aspect ratio of a blade also makes the LEV harder to anchor. This is a key difference between helicopter blades and typical biological wings.

The flow structures shown in Fig. 1 are consistent with those reported experimentally. To further identify the roles of the translational and rotational motions of a flapping wing in the formation of the LEV, computed velocity vector distributions on an end-view plane, at 60% of wing span for $Re = 6000$ (hawkmoth) are compared against those for $Re = 134$ (fruit fly) in Figs. 2a and 2b. The influence of wing rotation on the LEV is more evident at lower

Reynolds number (134) than at the higher one (6000). On the other hand, the higher Reynolds number (6000) yields much more pronounced axial flow at the core of the LEV, which together with the LEV forms a helical flow structure near the leading edge. In contrast, only very weak axial flow is detected for the lower Reynolds number (134). Figures 2c and 2d illustrate the pressure gradient contours on the wing of a fruit fly model and a hawkmoth model, respectively. Compared to hawkmoths, fruit flies, at a Reynolds number of 100–250, cannot create as steep pressure gradients at the vortex core. Nevertheless, they seem to be able to maintain a stable LEV during most of the down- and upstroke. Although the LEV on a hovering hawkmoth's wing breaks down in the middle of the downstroke, the LEV on the hovering fruit fly's wing stays attached during the entire downstroke, eventually breaking down during the subsequent supination.

The delta wing owes much of the lift that it is able to generate to the vortex flow, which initiates at the leading edge of the wing and rolls into a large core over the leeward side. The vortex core contains substantial axial velocity component with low pressure, and hence generates lift. This high flow velocity in the core of the vortex is a region of low pressure, which generates a suction, that is, lift. For a delta wing placed at high angles of attack, vortex breakdown occurs causing the destruction of the tight and coherent vortex. The diameter of the core increases, and the axial velocity component is no longer unidirectional. With the loss of axial velocity the pressure increases, and consequently, the wing loses lift. The literature on the subject is immense, and for a more general presentation of the various aspects of vortex breakdown, we refer the reader to several review articles [10–12]. For a fixed wing, an important trend is that at a fixed angle of attack, if the swirl is strengthened, then vortex breakdown occurs at lower Reynolds numbers. On the other hand, a weaker swirling flow tends to break down at a higher Reynolds number. Because the fruit fly exhibits a weaker LEV, from this viewpoint, it tends to better maintain the vortex structure than a hawkmoth, which creates a stronger LEV. Of course, the link regarding the vortex breakdown between a fixed and a flapping wing, if any, needs to be systematically investigated.

The LEV is a common feature associated with low Reynolds number flapping wing aerodynamics; the flow structures are influenced by the swirl strength and the Reynolds number, as well as the rotational rates. Its effectiveness in promoting lift is correlated with a flyer's sizes. As reviewed in [13,14] and highlighted in [15,16], in addition to the LEV, numerous issues related to the interplay among wing structures (including its anisotropic deformability), flapping kinematics, large vortex structures, and Reynolds number remain unresolved. These issues are critical for advancing concepts and technologies for future macro air vehicles and should be investigated.

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