

Aerodynamic analysis of insect-like flapping wings in fan-sweep and parallel motions with the slit effect

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ABSTRACT

In this study, the aerodynamic performance of flapping wings using a parallel motion was investigated and compared with the insect-like “fan-sweep” motion, and the effect of adding a slit to the wings was analyzed. First, numerical simulations were performed to analyze the wing aerodynamics of two flapping motions with equivalent stroke amplitudes over a range of pitching angles based on computational fluid dynamics (CFD). The simulation results indicated that flapping wings with a rapid and short parallel motion achieved better lift and efficiency than those of the fan-sweep motion while maintaining the same aerodynamic characteristics regarding stall delay and leading-edge vortices. For a parallel motion with a pitching angle of 25° and 100 mm stroke amplitude, the wings generated an average lift of 8.4 gf with a lift-to-drag ratio of 1.06, respectively, which were 1.8% and 26% greater than those of the fan-sweep motion with a corresponding 96° stroke amplitude. This situation was reversed when the pitching angle and stroke amplitude were increased to 45° and 144° for the fan-sweep motion, which was equivalent to the parallel motion with a 150 mm stroke amplitude. The slit effect in the parallel motion was also evaluated, and the CFD results indicated that a slit width of 1 mm (1/50 wing chord) increased the lift of the wing by approximately 27% in the case of the 150 mm stroke amplitude. Further, the slit width slightly influenced the lift and aerodynamic efficiency.

1. Introduction

Airflow separation occurs on fixed-wing surfaces at large angles of attack (AoA) beyond the stall angle, causing a dramatic lift coefficient reduction but an increase in drag. Many flying animals have demonstrated that significantly high lift coefficients can be achieved by flapping wings. For example, a hummingbird can achieve stable hovering by flapping its wings at a large AoA (greater than 30°) with the so-called “∞-shape” kinematics of motion in a nearly horizontal plane [Fig. 1(a)]. From the top view [Fig. 1(b)], the pair of wings reciprocates back and forth around the wing root in a fan-sweep motion to generate a high aerodynamic lift [1–3].

Over several decades of experimental and theoretical studies of flying animals, such as insects and hummingbirds, researchers have gained in-depth knowledge of the mechanism of the high-lift aerodynamics generated by flapping wings. In an experimental study, Ellington et al. [4] observed the formation and change of vortices during the fluttering of hawkmoth wings and established a 10× magnification model. The airflow forms a strong vortex around the upper surface of the leading edge (LE) when the flapping wings are at a large AoA. The appearance

of the LE vortex (LEV) [5–7] enhances the circular vectors around flapping wings, resulting in a low-pressure region on the upper surface near the LE, which significantly enhances the lift. Dickinson and Gotz [5] measured the changes in aerodynamic forces when hummingbird-like wings accelerated rapidly at low Reynolds numbers. The results showed that the LEV influences the wing movements of two chord lengths. Shahzad [8] and Han [9] verified that the appearance of the LEV increases the number of flapping wings' circular rectors, causing a low-pressure region on the upper surface near the LE, which significantly enhances the lift. Chin and Lentink [10] suggested that the LEV can be divided into two regions: the main LEV and a more separate three-dimensional (3D) tip region. The flow profiles in the 3D tip region differ from those in the main LEV. In summary, numerous studies have shown that the LEV is an essential contributor to the high lift of insects' flapping wings.

In a steady two-dimensional (2D) flow field, the LEV can separate from the wing after a short period and can cause a wing stall. As flapping wings usually flap in a repeating cycle at a certain frequency, the wing moves in one direction over a very short period and then stops

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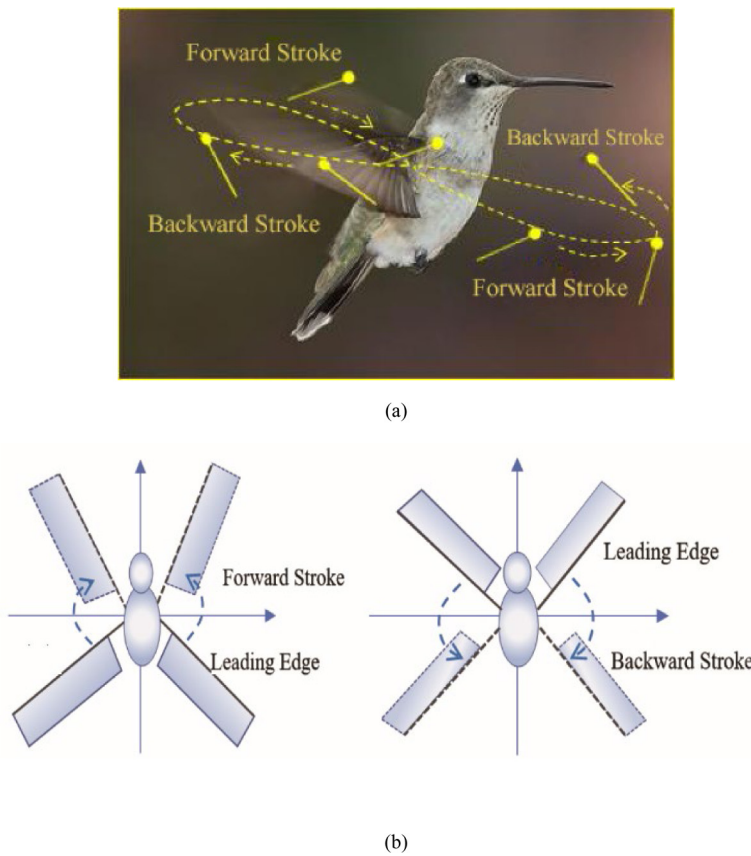


Fig. 1. (a) Side view of flapping wing “∞-shape” motion and (b) top view of fan-sweep motion of a hummingbird in hovering flight.

and reverses to prevent a wing stall. This phenomenon is called the “stall delay mechanism” [11–14] and is another essential characteristic of the high lift generated by flapping wings. Su and Yin [15] revealed that the effect of wing deformation can weaken the wake capture mechanism and can promote the “stall delay mechanism.” Ellington [4] also found that a spanwise flow [16,17] can be generated at the LE by increasing the flapping and flow velocities in the spanwise direction for 3D flapping wings with a small aspect ratio. The spanwise flow makes the LEV converge with the wingtip vortex [18–25] at the wingtip, depressing the LEV further increase and shedding. DeVoria and Mohseni [26] reported that the wingtip vortex size extends only up to 1.4–1.5 chord lengths from the tip. Therefore, vertical advection is only effective in maintaining LEV attachment. Moreover, the spanwise flow stabilizes the LEV on the wing surface for a longer period, which is an additional characteristic of the high lift of insects’ flapping wings. Owing to the essential roles of the LEV and stall delay mechanism in the high-lift generation of a flapping wing at low Reynolds numbers, many scholars have explored the fluid-dynamic properties of these phenomena recently [27–32].

As shown in Fig. 1, the relative velocity of the fan-sweep motion along the span increases linearly from zero at the wing root to the maximum at the wingtip. The inner wing, which has a relatively low motion velocity, is much less effective than the outer wing in terms of lift generation. Birch and Dickinson [33] also performed fruit fly model experiments that showed that a limiting spanwise flow with fences and edge baffles does not cause the LEV detachment. This illustrates that for small-scale flapping wings [34] and a low Reynolds number, the airflow along the wingspan is weak and the spanwise flow is neither a necessary condition nor the main contributor to the stall delay mechanism. Experimental data [8] also support an alternative hypothesis that the downward flow induced by the tip vortices inhibits the LEV increase. Combined with the translation and rotation of flapping wings in the parallel mode, the downward flow induced by the wingtip vortices still

exists, indicating that the parallel flapping mode offers a certain degree of stall delay.

It can be inferred from the above studies that the fan-sweep flapping motion is not necessarily the optimal choice for aerodynamic lift and efficiency. In this study, the kinematics of an alternative parallel motion is proposed, whereby the entire wing from the root to tip flaps forward and backward in the horizontal plane. As each section of the wing moves with the same stroke amplitude and velocity in a cycle, the wing is aerodynamically equally effective along the span. The LEV will also form on the flapping wing in parallel motion, and the aerodynamic characteristics of the delayed stall can be maintained. However, the suppression effect of the LEV shedding can be largely reduced because of the lack of spanwise flow, which means that the delayed stall effect exists within a limited range of stroke amplitudes. Therefore, a smaller stroke amplitude is expected for flapping wings in parallel motion. Thus, we investigated the aerodynamic performance of two motion types using computational fluid dynamics (CFD) and compared them with the fan-sweep motion subject to the same flapping area or an equivalent stroke amplitude. To identify the optimal flapping motion with the maximum aerodynamic lift or efficiency, the stroke and pitching amplitudes were examined over a typical range for insect-like flapping wings.

We also evaluated the effect of a slit in flapping wings on the aerodynamic performance in the parallel motion. Simulation results demonstrated that improvements of more than 20% in aerodynamic performance can be achieved when the wings include a slit.

2. Theoretical analysis

2.1. Insect-like fan-sweep flapping and parallel motions

Fig. 2 illustrates the fan-sweep motion as the simplified motion of a hummingbird-like flapping wing in the x - y - z coordinate system.

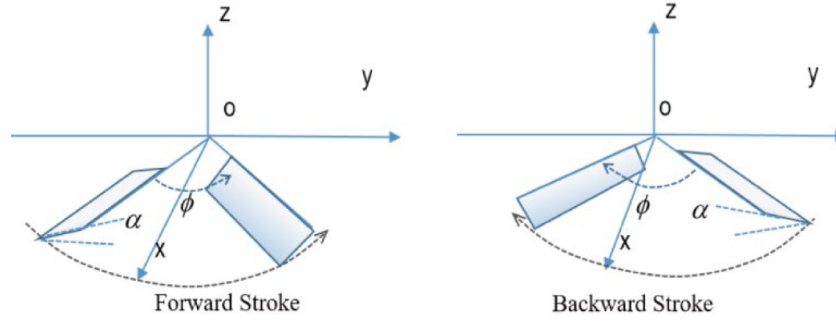


Fig. 2. Simplified hummingbird-like fan-sweep motion of a flapping wing.

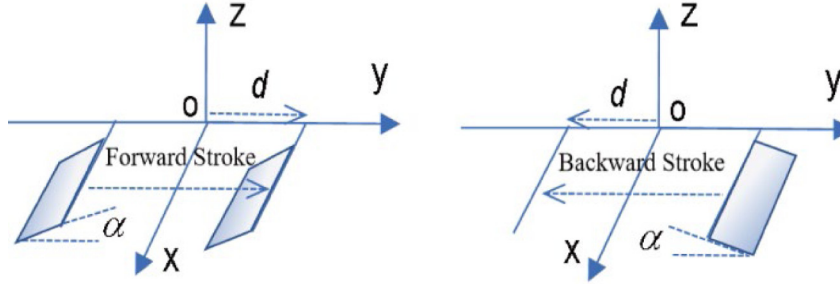


Fig. 3. Schematic of the flapping wing in the parallel motion.

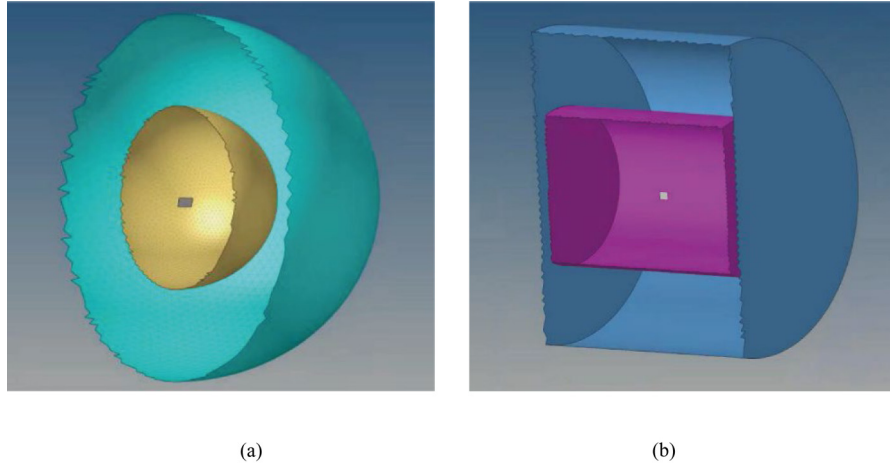


Fig. 4. Far-field diagrams of the CFD model for (a) fan-sweep motion and (b) parallel motion.

The kinematics of motion is a combination of the wings' flapping and pitching variations with two degrees of freedom. The wings rotate around the z -axis at a specified pitching angle α in the forward stroke and then rotate backward at a pitching angle of $180^\circ - 2\alpha$ around the wing's front spar after reaching the maximum stroke amplitude in the forward position. A cycle of flapping motion is completed when the wing reaches the maximum stroke amplitude at the backward position. The motion then repeats continuously periodically at a specified frequency.

The fan-sweep flapping and pitching motions can be expressed as follows:

$$\phi = \Phi \sin(2\pi f \times t), \quad (1)$$

$$\alpha = A \cos(2\pi f \times t), \quad (2)$$

where ϕ and Φ denote the flapping angle and maximum amplitude, respectively, α denotes the wing pitching angle measured in the x - y plane, A denotes the maximum pitching amplitude, f denotes the flapping frequency, and t denotes time.

Fig. 3 shows a flapping wing in the parallel motion in the x - y - z coordinate system. The entire wing moves forward and backward in a parallel path along the y -axis periodically. Taking the coordinate origin o as the starting point, the wing moves through its forestroke at a specified pitching angle α until the maximum stroke amplitude is reached. Then, the flapping wing reverses and moves through its backstroke at a pitching angle of $180^\circ - \alpha$, which is achieved by rotating the wing spar around the x -axis at a reversed angle of $180^\circ - 2\alpha$. The cycle of flapping motion ends when the backstroke is completed and the wing is back at the starting position.

The flapping motion of the parallel mode can be expressed as follows:

$$d = \frac{D}{2} \sin(2\pi f \times t), \quad (3)$$

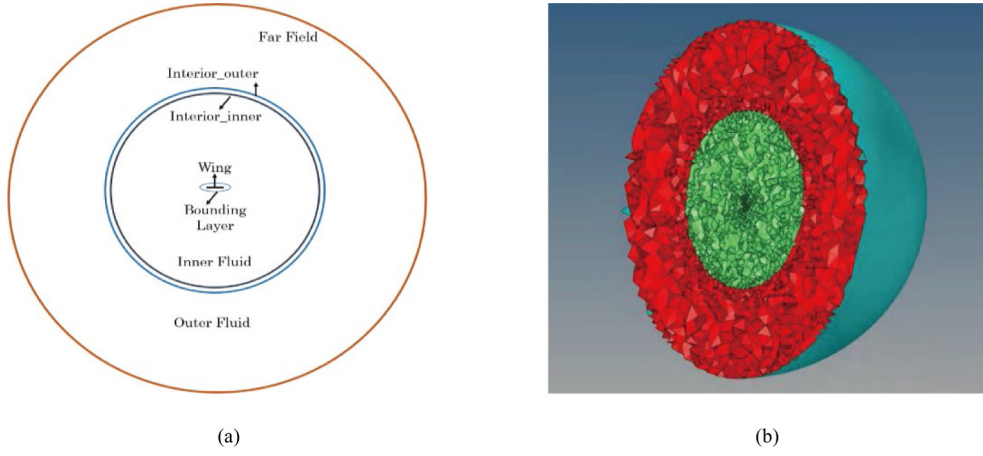


Fig. 5. CFD grid structure of the (a) flow field and (b) mesh for the fan-sweep wing motion.

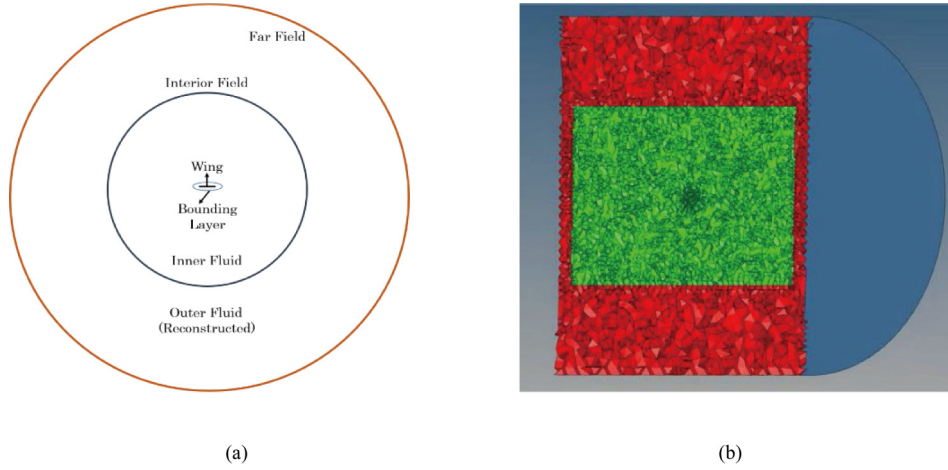


Fig. 6. CFD grid structure of the (a) flow field and (b) mesh for the parallel wing motion.

```
#include <stdio.h>
#include <math.h>
#include "udf.h"
static double pitch_angle;
static double time_previous;
static double roll_angle;

DEFINE_ZONE_MOTION(motion_1, omega, axis, origin, velocity, time, dt)
{
    real phiA, alfu, alfd, n, r, t, pi, delt, phase;
    real alfA, phi, alf, dphi, dalf, k, areaS, amplitude;
    double motion[] = {0, 0, 0, 0};
    double omega_0, omega_1;
    FILE *fid;
```

Fig. 7. User-defined function scripts for the CFD models of different motion types.

where d represents the distance of the wing root from the origin (starting point) in the y -direction at time t and D denotes the maximum stroke amplitude. The pitching angle remains the same as that in Eq. (2).

2.2. CFD model of the 3D wing

To evaluate and compare the aerodynamic performance of flapping wings in the fan-sweep and parallel motion modes, a CFD model was constructed using the commercial software ANSYS-FLUENT. In particular, a 3D flapping wing model with a 100 mm semispan and a 50 mm chord length was established. Fig. 4 shows the far-field diagrams of

the CFD model for the flapping wing in the fan-sweep motion modeled in a spherical field and the parallel motion modeled in a cylindrical field. The ratio of the radius of the far-field circle to the wingspan was set to 10 to minimize the boundary effects on the flow field [35]. The aerodynamic force generated by the wing at each moment during a flapping cycle was calculated by solving the Navier–Stokes equations at discrete time/space points.

To avoid a time-consuming reconstruction and poor-quality dynamic meshing [32], we employed the algebraic mesh generation method based on the transfinite interpolation theory to generate a tetrahedral sliding mesh [36,37] around the wing in the fan-sweep flapping motion. This method is highly adaptable to the flapping wing shape and is well suited to unsteady aerodynamic simulations. The $K-\omega$ shear-stress transport turbulence solver [38] was used in the CFD model. As shown in Fig. 5(a), the flow field was divided into inner and outer flow fields. The inner flow field moved with the flapping wing motion, and hence, it was not reconstructed during the calculation process. The entire structure comprises five surface meshes and three volume meshes. A grid resolution study was conducted before executing the flapping wing CFD simulation to obtain the unsteady aerodynamic solution.

The sliding mesh method is unsuitable for flapping wings in parallel motion. As shown in Fig. 6(a) and (b), the entire structure comprises four surface meshes and three volume meshes. The inner flow moved with the wing, and the outer flow was reconstructed at every time step during the flapping motion of the wing model.

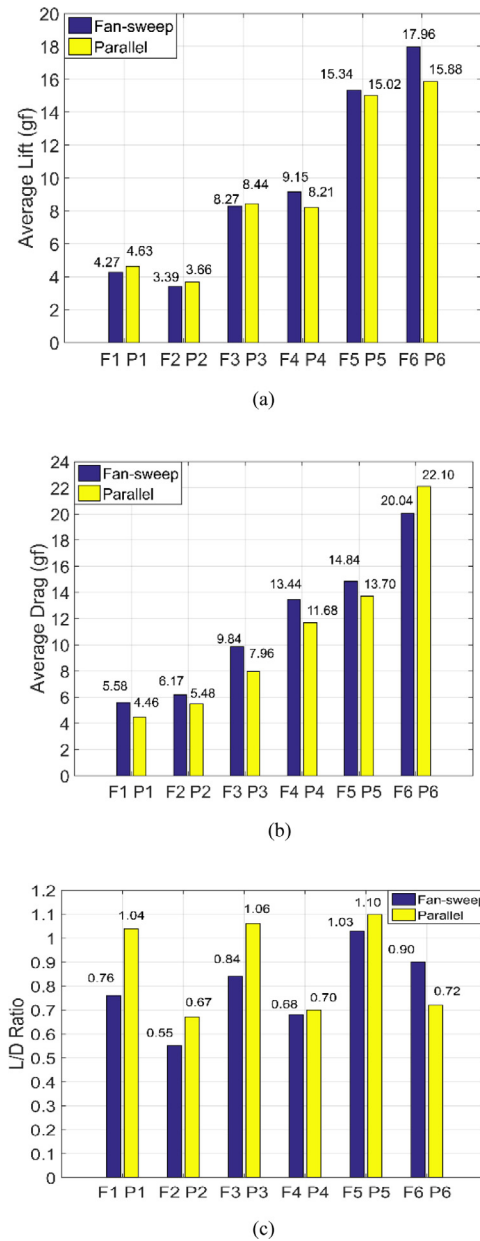


Fig. 8. Aerodynamic results for average (a) lift L , (b) drag D , and (c) lift/drag ratio L/D of the flapping wings in different motion types.

To implement the wing motion in the CFD simulations, two user-defined functions were scripted: NACA 4-Digits and DEFINE_ZONE_MOTION functions. The NACA 4-Digits function was used to define a specified NACA airfoil geometry, and the DEFINE_ZONE_MOTION function was used to define the wing motion as a rigid body (Fig. 7). For the CFD models, the influence of the grid density, time step, and computational domain size on the solution was considered. According to awing dimension of 100×50 mm, the radii of the inner and outer flow fields were set to 800 and 1,600 mm, respectively. A dimensionless time-step size of 0.002 was set, and 500 calculations were performed within one flapping cycle.

3. Aerodynamic results and discussion

The aerodynamic analysis of flapping wings was performed under the condition that the wings in the fan-sweep and parallel motions sweep the same volume of space at the same pitching angle in a

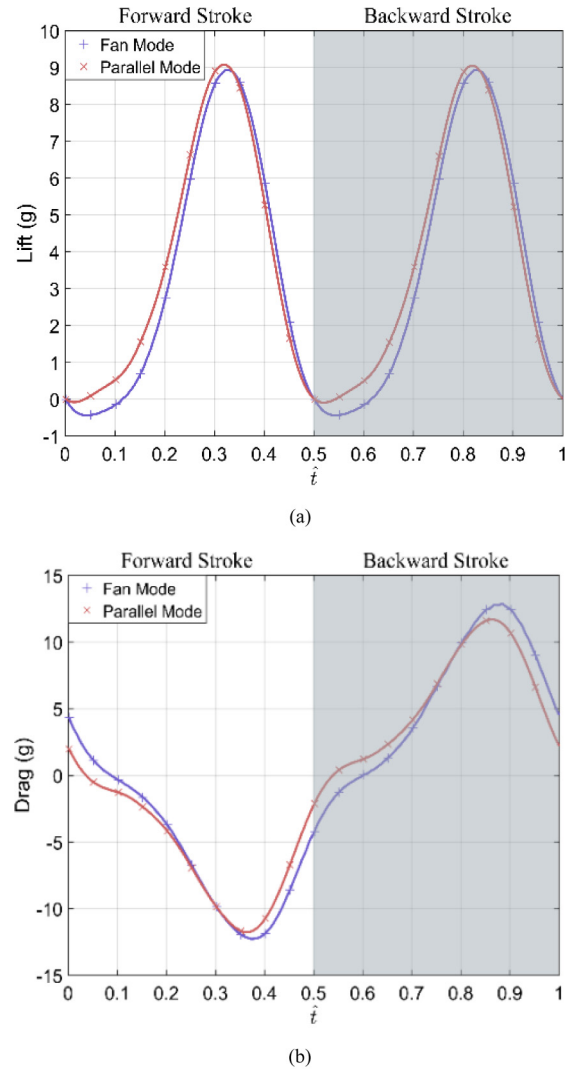


Fig. 9. (a) Lift force and (b) drag force produced by one cycle of the flapping wing in cases F_2 and P_2 ($\bar{t}$ refers to dimensionless time).

flapping cycle. Table 1 presents the combinations of pitching angle ranges and equivalent stroke amplitudes considered in this study for the fan-sweep and parallel motions. A pitching angle of 25° – 155° represents a wing pitching angle of 25° in the forestroke and 155° ($=180^\circ-25^\circ$) in the backstroke (a similar definition for 45° – 135°). The equivalent stroke amplitude for the space swept by a flapping wing in the fan-sweep motion in six cases, namely, F_1 – F_6 , is equal to that for the space swept by the wing at the same pitching angle in the parallel motion in cases P_1 – P_6 , respectively, i.e., 48° versus 50 mm, 96° versus 100 mm, and 144° versus 150 mm.

The average aerodynamic lift L , drag D , and lift/drag ratio L/D of flapping wings in all six cases are shown in Fig. 8. In general, L and D increase with the stroke amplitude for both types of flapping motions in cases F_1 – F_6 and P_1 – P_6 . For the smallest stroke amplitude and pitching angle (25° – 155°), L and L/D are, respectively, 8.4% and 36.8% larger in case P_1 (a stroke amplitude of 50 mm) than in case F_1 (an equivalent stroke amplitude of 48°), and the lift difference between the two cases is 0.36 gf. When the pitching angle increases to 45° – 135° , L and L/D decrease in both flapping motion types. Nevertheless, L and L/D in case P_2 are, respectively, 7.9% and 21.8% larger than those in case F_2 , and the lift difference between the two cases is 0.27 gf. When the stroke amplitude is doubled (100 mm and equivalent to 96°) in cases P_3 , P_4 , F_3 , and F_4 , the average L and L/D produced by the wings in both

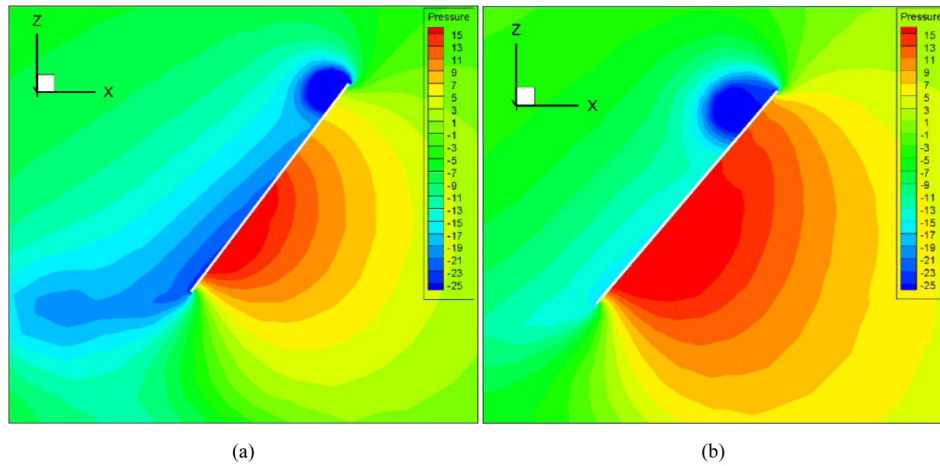


Fig. 10. Pressure distribution on the flapping wing at $\hat{t} = 0.35$ in the (a) fan-sweep motion and (b) parallel motion.

Table 1

Six cases of the flapping wing ($100 \times 50 \text{ mm}^2$) in the fan-sweep and parallel motions with different stroke amplitudes and pitching angles.

Fan-sweep	Case No	F ₁	F ₂	F ₃	F ₄	F ₅	F ₆
	Stroke amplitude	48°	48°	96°	96°	144°	144°
	Pitching angle	25°–155°	45°–135°	25°–155°	45°–135°	25°–155°	45°–135°
Parallel	Case No	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆
	Stroke amplitude	50 mm	50 mm	100 mm	100 mm	150 mm	150 mm
	Pitching angle	25°–155°	45°–135°	25°–155°	45°–135°	25°–155°	45°–135°

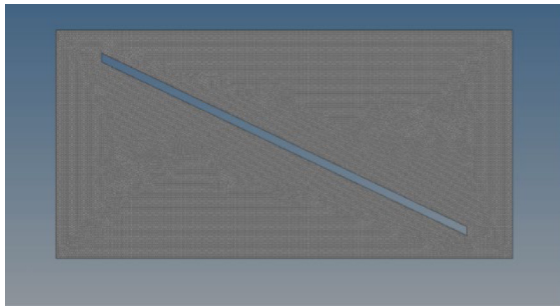


Fig. 11. Schematic of the wing with a slit.

flapping motion types increase significantly (approximately doubles). At a 25° pitching angle, L in case P₃ is only 1.8% larger than that in case F₃, but L/D is 26.2% larger. When the pitching angle increases to 45° (135° in backstroke), L increases in case F₄ but decreases in case P₄. L/D decreases in both flapping motion types. In case P₄, L is 10% smaller than that in case F₄, whereas L/D is 3% larger. When the stroke amplitude is tripled (150 mm and equivalent to 144°) in cases P₅, P₆, F₅, and F₆, the average L in both motion types also increases significantly (by a factor of more than three), whereas L/D does not change much. Nevertheless, compared with the fan-sweep motion at a 25° pitching angle, L in case P₅ is 2% smaller, and L/D remains 5.8% larger. When the pitching angle is increased to 45°, the parallel flapping motion loses its advantage in both average L and L/D . The average L and L/D produced by the wing in case F₆ are, respectively, 11.6% and 20% larger than those produced by the wing in the parallel motion in case P₆.

Fig. 9 demonstrates the instantaneous lift and drag forces produced over one cycle of the flapping wing at the 45°–135° pitching angle with a 48° stroke amplitude in the fan-sweep motion (case F₂) and parallel motion with an equivalent 50-mm stroke amplitude (case P₂). The results showed that the lift and drag of the wings in the forestroke

were symmetrical to those in the backstroke for both motion types. In addition, the maximum lift occurred near the midstroke at $\hat{t} = 0.32$ and 0.82 and had almost the same value in both cases. Fig. 9(a) demonstrates that the lift generated by the wing in the parallel motion (case P₂) reached an almost zero minimum value at $\hat{t} = 0.01$ and 0.51 but remained positive during the entire flapping cycle. The wing in the fan-sweep motion (case F₂) produced a small negative lift during the forestroke and backstroke transitions at $\hat{t} = 0 - 0.12$ and $\hat{t} = 0.5 - 0.62$, respectively. As shown in Fig. 9(b), the drag of the wing in the fan-sweep motion (case F₂) was larger than that in the parallel motion (case P₂) during the forestroke and backstroke transitions at $\hat{t} = 0 - 0.1$ and $\hat{t} = 0.5 - 0.6$, respectively, and after the maximum lift at $\hat{t} = 0.35 - 0.5$ and $\hat{t} = 0.85 - 1.0$.

In summary, the parallel motion produced higher aerodynamic lift and efficiency over most stroke amplitudes and pitching angles listed in Table 1, especially with stroke amplitudes of less than 100 mm and a 25° pitching angle. When the stroke amplitude and pitching angle increased to their maximum values (144°–150 mm and 45°), the fan-sweep motion (case F₆) performed better, with greater aerodynamic lift and efficiency, than the parallel motion did (case P₆).

To gain an insight into the results, the pressure on the flapping wing was captured and analyzed. Fig. 10 shows the pressure on the 2D wing sections in the middle of the semispan at $\hat{t} = 0.35$, when the maximum lift and drag forces occurred (see Fig. 9). The pressure on the upper and lower surfaces of the wing in the fan-sweep motion [Fig. 10(a)] differed from that in the parallel motion [Fig. 10(b)]. Although the LEV was still fully attached at this moment for the parallel motion, the average negative pressure (−19.8 Pa) on the upper wing surface was smaller than that in the fan-sweep motion (−24.7 Pa). However, the area of positive pressure and the average value (13.5 Pa) on the lower wing surface in the parallel motion were clearly larger than those in the fan-sweep motion (average 9.1 Pa). Therefore, the average pressure difference in the parallel motion (33.3 Pa) was slightly smaller than that in the fan-sweep motion (33.8 Pa) at $\hat{t} = 0.35$ but only by 1.5%.

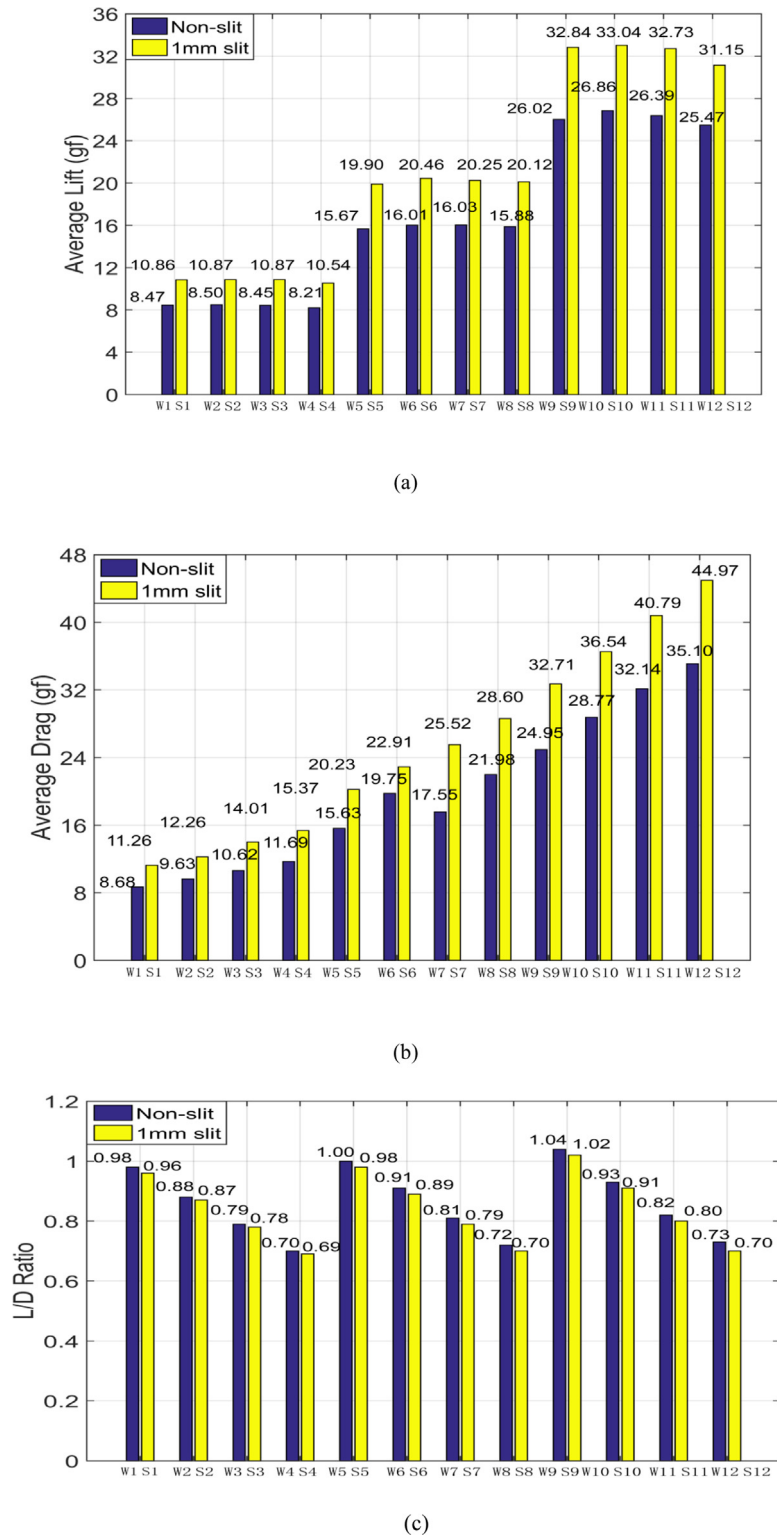


Fig. 12. Aerodynamic results for average (a) lift L , (b) drag D , and (c) lift/drag ratio L/D of the flapping wings with and without a slit in the parallel motion.

4. Slit effect on aerodynamic performance of flapping wings

4.1. Wing with a 1-mm slit in parallel motion

To evaluate the effectiveness of a slit on the wing [39,40] for lift enhancement, a slit of 1/50 chord width (1 mm) was introduced to the

flapping wing. The slit ran along the diagonal line from the wing root to the tip close to the trailing edge (Fig. 11).

The CFD model of the wing in the parallel motion was updated, and the results were compared with those from the wing without a slit. To obtain further details of the slit effect, the stroke amplitude ranges were extended (100, 150, and 200 mm) and the pitching angle was extended to four different values (45°, 40°, 35°, and 30°). This yielded 12 cases

Table 2

Twelve cases of the flapping wing in the parallel motion with and without a slit (1 mm) in extended ranges of stroke amplitudes and pitching angles.

Wing	Stroke amplitude (mm)	Pitching angle			
		30°–150°	35°–145°	40°–140°	45°–135°
Without a slit	100	W ₁	W ₂	W ₃	W ₄ (P ₄)
	150	W ₅	W ₆	W ₇	W ₈ (P ₆)
	200	W ₉	W ₁₀	W ₁₁	W ₁₂
With a 1-mm slit	100	S ₁	S ₂	S ₃	S ₄
	150	S ₅	S ₆	S ₇	S ₈
	200	S ₉	S ₁₀	S ₁₁	S ₁₂

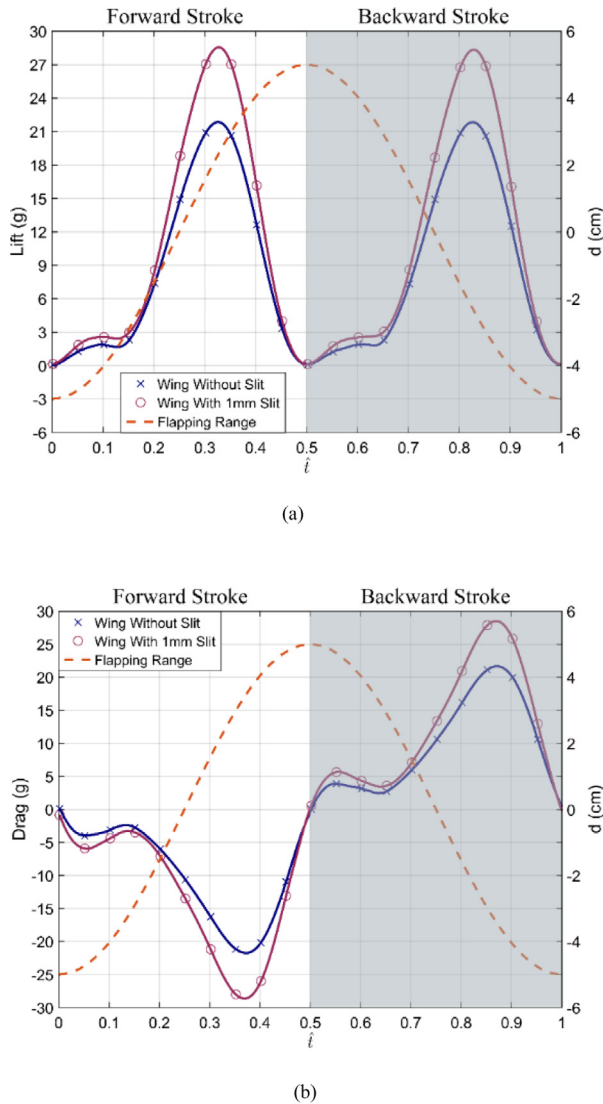


Fig. 13. (a) Lift and (b) drag forces of the wings with and without a slit for a 100 mm stroke amplitude at a pitching angle of 35°–145°.

of parallel motion with a combination of stroke amplitudes and pitching angles (Table 2). These 12 cases include P₄ and P₆ (a stroke amplitude of 100 mm at a pitching angle of 45°–135°) (Table 1), which provides a reference.

The resulting average aerodynamic lift L , drag D , and lift/drag ratio L/D of the flapping wings are presented in Fig. 12. The results showed that the average L and D of wings with and without a slit increased significantly with the stroke amplitude expansion at any

pitching angle, which agrees with the cases in Table 1. L varied slightly at different pitching angles, although the maximum L corresponded to a pitching angle of 35°–145°. As D decreased with the pitching angle, L/D increased significantly as the pitching angle was reduced for all cases. Second, L was significantly higher in the 1-mm slotted wing, increasing by 28.4%, 26.7%, and 22.3% compared with the baseline wing without a slit for stroke amplitudes of 100, 150, and 200 mm, respectively. In addition, the slit in the wing increased D by almost the same percentage compared with baseline. This produced a difference of ~4.2% in L/D between the two types of wings. Such a result indicates that wing slits increase the aerodynamic lift over an increased range of stroke amplitudes but do not enhance aerodynamic efficiency.

From the aerodynamic force–time history in a flapping cycle [Fig. 13(a)], the minimum lift occurred at $\hat{t} = 0$ and 0.5, respectively, in the forestroke and backstroke transition periods for the two types of wings, and the maximum lift occurred at $\hat{t} = 0.33$ and 0.83, close to the middle of the stroke cycle. The results also showed that the maximum lift force (28.56 g) of the 1 mm slotted wing increased by 28% compared with the maximum lift (22.3 g) of the baseline wing without a slit, which was the main reason for the slotted wing generating 27.8% greater L than that of the baseline wing. Similar results can be found for the drag force in Fig. 13(b), where the maximum drag occurred at $\hat{t} = 0.37$ and 0.87, close to 3/4 of the forestroke and backstroke, respectively. The difference in the average drag forces between the baseline and slotted wings was greater than 29%.

Figs. 14 and 15 show the pressure of the 2D section in the middle of the two types of wings for a 100-mm stroke amplitude at a pitching angle of 35°–145°. The results captured the process of the LEV forming, growing, and detaching from the two types of wings during the period $\hat{t} = 0.25 - 0.6$. Although the LEV of the slotted wing (see Fig. 15) was initiated slightly later, it increased rapidly, with a larger negative-pressure area and a longer attachment area on the upper surface than those of the baseline wing (Fig. 14), especially during the period $\hat{t} = 0.35 - 0.4$. Further, the LEV started to detach and shed from the baseline wing's upper surface at $\hat{t} = 0.35$. However, the LEV on the slotted wing was enhanced by the flow from the lower surface through the slit and increased to a maximum at the critical moment. On the lower surface, the positive-pressure area across the slotted wing was larger than that of the baseline wing during the period $\hat{t} = 0.25 - 0.45$. For example, the pressure difference of the slotted wing was 76.5 Pa (26.6 Pa, -49.9 Pa), which was 11.8% higher than the 68.4 Pa difference (21.6 Pa, -46.8 Pa) of the baseline wing. Therefore, the pressure difference between the upper and lower surfaces, and the induced lift and drag forces from the slotted wing were significantly higher than those of the baseline wing (Fig. 12).

4.2. Effect of the slit width

As the wing slit is clearly effective, a further study was conducted to compare slit widths of 1 mm (1/50 chord), 2 mm (1/25 chord), and 5 mm (1/10 chord). Cases S₁–S₄, as shown in Table 2 for the wing with a 1 mm slit and 100 mm stroke amplitude, were selected for comparison against several cases with 2 and 5 mm slits (Table 3).

The resulting aerodynamic forces and efficiencies are shown in Fig. 16. The lift L and drag D forces decreased slightly when the slit

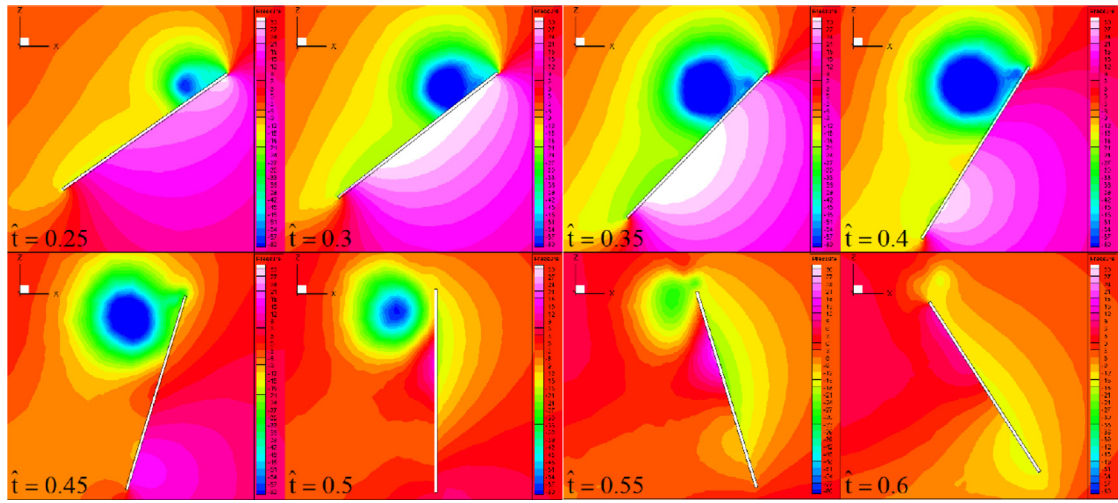


Fig. 14. Pressure plot of the baseline wing in a 100 mm parallel stroke amplitude at a pitching angle of 35°–145° in the period $\hat{t} = 0.25 - 0.6$.

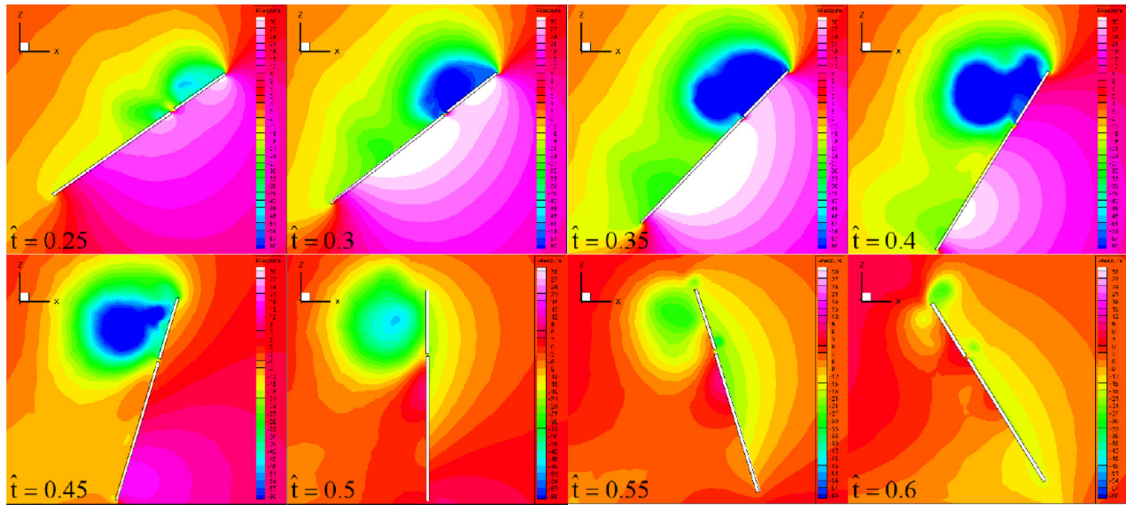


Fig. 15. Pressure plot of the wing with a slit in a 100 mm parallel stroke amplitude at a pitching angle of 35°–145° in the period $\hat{t} = 0.25 - 0.6$ (half a flapping cycle).

Table 3

Cases of the flapping wing with three different slit widths (1 mm, 2 mm, and 5 mm) with a 100 mm stroke amplitude and four pitching angles.

Slit width (mm)	Stroke amplitude (mm)	Pitching angle			
		30°–150°	35°–145°	40°–140°	45°–135°
1	100	S_1	S_2	S_3	S_4
2	100	R_1	R_2	R_3	R_4
5	100	Q_1	Q_2	Q_3	Q_4

width was increased to 2 and 5 mm at all selected pitching angles. D increased with the pitching angle [Fig. 16(b)], whereas L changed slightly [Fig. 16(a)], and so, L/D decreased as the pitching angle increased [Fig. 16(c)]. However, at each pitching angle, L/D changed slightly with variations in the slit width [Fig. 16(c)]. Considering the pitching angle of 35°–145° as an example, with slit widths of 2 mm (case R_2) and 5 mm (case Q_2), L was only 2.3% and 2.0% smaller, respectively, than that in the wing with a 1 mm slit (case S_2), whereas L/D remained at 0.87.

Fig. 17 presents the details of the lift and drag forces produced by wings with different slit widths in a flapping cycle. The lift and drag forces were very similar, except for the peak values during the periods $\hat{t} = 0.3 - 0.4$ and $\hat{t} = 0.8 - 0.9$, where the maximum peak values were produced by the 1 mm slotted wing.

To investigate the effect of the slit width on the aerodynamic performance of flapping wings, the 2D section pressure on wings with different slit widths was captured at $\hat{t} = 0.32$ (Fig. 18). At this point in the forestroke, with a pitching angle of 35°–145° in the parallel motion and a 100 mm stroke amplitude, the lift and drag forces produced by wings with different slit widths were close to their peak values. The negative-pressure area on the upper surface and the positive-pressure area on the lower surface of the 1 mm slotted wing were greater than those of the 2 and 5 mm slotted wings. For the 1 mm slotted wing, a vortex was generated by the airflow blowing from the lower surface through the slit [Fig. 18(a)], and this merged with and enhanced the LEV. However, for the 2 and 5 mm slotted wings, the airflow blowing through the slit generated a separate vortex rotating in the opposite direction to the LEV. Therefore, the LEV strength was reduced [Figs. 18(b) and 18(c)]. Although the slit produced an additional vortex

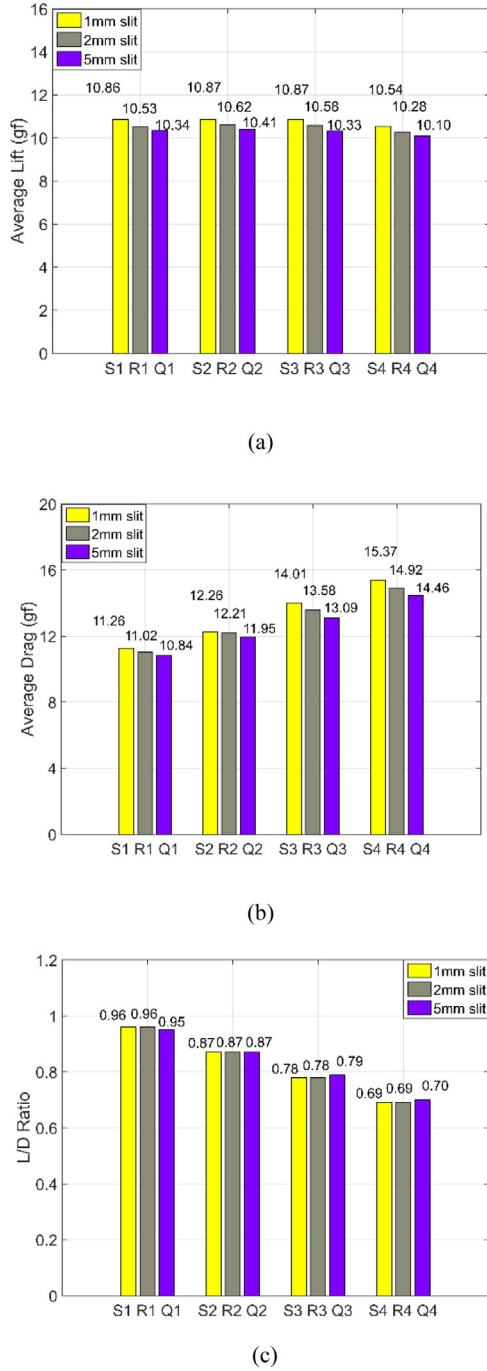


Fig. 16. Aerodynamic results for average (a) lift L , (b) drag d , and (c) lift/drag ratio L/d of the flapping wings with different slit widths (1 mm, 2 mm, and 5 mm).

and negative-pressure area after the slit, it weakened the LEV and could lead to earlier vortex detachment and shedding for the 5 mm slit [Fig. 18(c)]. Table 4 lists the corresponding pressure values of the upper and lower surfaces of the wings at $\hat{t} = 0.32$. The pressure difference between the upper and lower surfaces of the wings gradually decreased as the slit width increased.

In summary, the pressure difference between the upper and lower surfaces and the resulting wing lift tended to decrease as the slit width increased. The results also indicated that the slit width should be optimized together with its location and that the LEV depended on the wing dimension and flapping motion.

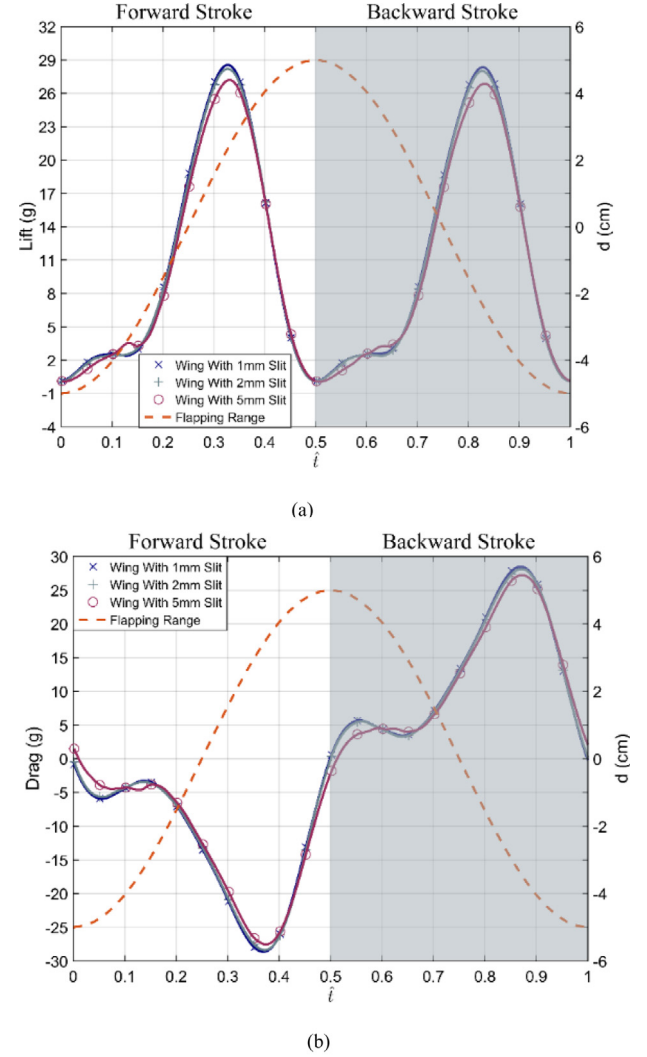


Fig. 17. (a) Lift and (b) drag force of the wings with different slit widths.

Table 4

Pressure values of wings with different slit widths.

Wing width	1 mm	2 mm	5 mm
Pressure on the upper surface	-49.9	-49.2	-47.0
Pressure on the lower surface	26.6	26.0	24.8
Pressure difference	76.5	75.2	71.8

5. Conclusions

From the results of the present investigation of the kinematics of motion and the slit effect on the aerodynamic performance of flapping wings, the following conclusions can be drawn.

- The parallel motion provides alternative motion kinematics for a flapping wing, producing comparable aerodynamic lift and efficiency to the conventional insect-like fan-sweep motion.
- For two motion types, the lift produced by the wing increases almost linearly with the stroke amplitude, thereby achieving higher lift but with lower efficiency.
- Compared with the fan-sweep motion, the aerodynamic wing lift and efficiency in the parallel motion are slightly higher within a limited range of stroke amplitudes (≤ 100 mm for the parallel motion or $\leq 96^\circ$ for the fan-sweep motion) and pitching angles ($\leq 25^\circ$) but become lower when the stroke amplitude and pitching angle are outside these ranges.

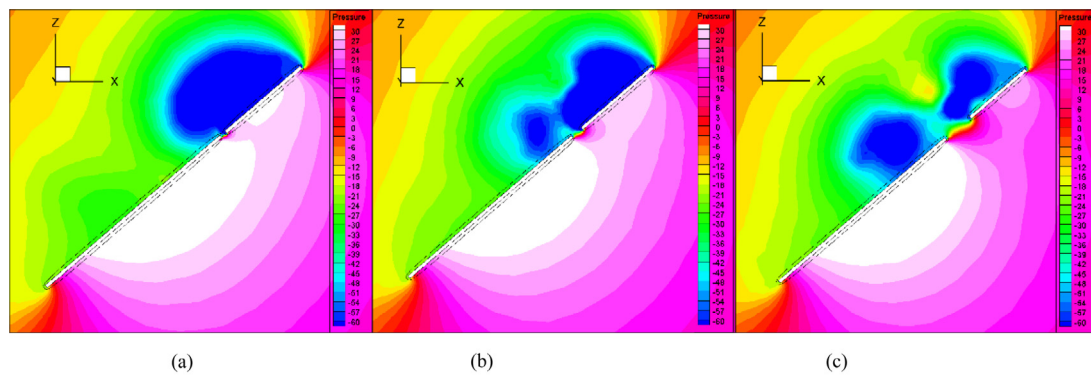


Fig. 18. Pressure plot on a 2D section of the wings with slit widths of (a) 1, (b) 2, and (c) 5 mm, captured at $\hat{t} = 0.32$ in the parallel motion at a pitching angle of 35° – 145° .

- Adding a slit on the wing is highly effective in increasing the aerodynamic lift but does not enhance aerodynamic efficiency. For the parallel motion, the average lift with a 1-mm slit increases significantly compared with the baseline wing (by 28.4%, 26.7%, and 22.3% for stroke amplitudes of 100, 150, and 200 mm, respectively). The lift becomes greater than that in the fan-sweep motion over the entire range of flapping amplitudes and pitching angles.
- Increasing the slit width to 2 and 5 mm reduces slit effectiveness slightly, with the average lift decreasing by less than 5% compared with the 1-mm slotted wing, and the influence on aerodynamic efficiency is negligible.
- Further study of the airflow and pressure of flapping wings revealed that the airflow blowing through the slit could enhance or weaken the LEV strength. Nevertheless, the slit is beneficial for the wings' aerodynamic performance. It is possible to gain greater enhancements by optimizing the slit width and location according to the flapping motion. In addition, a further experimental test will be performed to validate the simulation results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.birob.2022.100046>.

References

- [1] J. Yao, K.S. Yeo, Free hovering of hummingbird hawkmoth and effects of wing mass and wing elevation, *Comput. Fluids* 186 (2019) 99.
- [2] H.R. Vejdani, D.B. Boerma, S.M. Swartz, K.S. Breuer, The dynamics of hovering flight in hummingbirds, insects and bats with implications for aerial robotics, *BioinspirBiomim* 14 (2018) 016003.
- [3] D.R. Warrick, B.W. Tobalske, D.R. Powers, Aerodynamics of the hovering hummingbird, *Nature* 435 (2005) 1094.
- [4] C.P. Ellington, C. VandenBerg, A.P. Willmott, A.L.R. Thomas, Leading-edge vortices in insect flight, *Nature* 384 (1996) 626.
- [5] M.H. Dickinson, K.G. Gotz, Unsteady aerodynamic performance of model wings at low Reynolds numbers, *J. Exp. Biol.* 174 (1993) 45.
- [6] J.D. Eldredge, A.R. Jones, *Leading-edge vortices: Mechanics and modeling*, 2019.
- [7] F.T. Muijres, L. Christoffer Johansson, Y. Winter, A. Hedenström, Leading edge vortices in lesser long-nosed bats occurring at slow but not fast flight speeds, *BioinspirBiomim* 9 (2014) 025006.
- [8] A. Shahzad, F.B. Tian, J. Young, J.C.S. Lai, Effects of wing shape, aspect ratio and deviation angle on aerodynamic performance of flapping wings in hover, *Phys. Fluids* 28 (2016) 111901.
- [9] J.S. Han, H.Y. Kim, J.H. Han, Interactions of the wakes of two flapping wings in hover, *Phys. Fluids* 31 (2019) 021901.
- [10] D.D. Chin, D. Lentink, Flapping wing aerodynamics: From insects to vertebrates, *J. Exp. Biol.* 219 (2016) 920–932.
- [11] S.-P. Breton, F.N. Coton, G. Moe, A study on rotational effects and different stall delay models using a prescribed wake vortex scheme and NREL phase VI experiment data, *Wind. Energy* 11 (2008) 459.
- [12] C. Bruecker, C. Weidner, Influence of self-adaptive hairy flaps on the stall delay of an airfoil in ramp-up motion, *J. Fluids Struct.* 47 (2014) 31.
- [13] T.C. Corke, F.O. Thomas, Dynamic stall in pitching airfoils: Aerodynamic damping and compressibility effects, 2015.
- [14] A. Seifert, A. Darabi, I. Wyganski, Delay of airfoil stall by periodic excitation, *J. Aircr.* 33 (1996) 691.
- [15] X.H. Su, Z. Yin, Y.W. Cao, et al., Numerical investigations on aerodynamic forces of deformable foils in hovering motions, *Phys. Fluids* 29 (2017) 041902.
- [16] N. Phillips, K. Knowles, Formation of vortices and spanwise flow on an insect-like flapping wing throughout a flapping half cycle, *Aeronaut. J.* 117 (2013) 471.
- [17] Y. Hong, A. Altman, Lift from spanwise flow in simple flapping wings, *J. Aircr.* 45 (2008) 1206.
- [18] M.J. Churchfield, G.A. Blaisdell, Numerical simulations of a Wingtip vortex in the near field, *J. Aircr.* 46 (2009) 230.
- [19] J.H. Garcia-Ortiz, F.J. Blanco-Rodriguez, L. Parras, et al., Experimental observations of the effects of spanwise blowing on the wingtip vortex evolution at low Reynolds numbers, *Eur. J. Mech. B Fluids* 80 (2020) 133.
- [20] J.H. Garcia-Ortiz, A. Dominguez-Vazquez, J.J. Serrano-Aguilera, et al., A complementary numerical and experimental study of the influence of Reynolds number on theoretical models for wingtip vortices, *Comput. Fluids* 180 (2019) 176.
- [21] A. Lu, V. Tremblay-Dionne, T. Lee, Experimental study of aerodynamics and Wingtip vortex of a rectangular wing in flat ground effect, *J. Fluids Eng.* 141 (2019).
- [22] F.S. Pereira, L. Eca, G. Vaz, Simulation of Wingtip vortex flows with Reynolds-averaged Navier–Stokes and scale-resolving simulation methods, *AIAA J.* 57 (2019) 932.
- [23] D.J. Garmann, M.R. Visbal, P.D. Orkwis, Three-dimensional flow structure and aerodynamic loading on a revolving wing, *Phys. Fluids* 25 (2013) 034101.
- [24] S.H. Lee, M. Lahooti, D. Kim, Aerodynamic characteristics of unsteady gap flow in a bristled wing, *Phys. Fluids* 30 (2018) 071901.
- [25] Z.R. Carr, C. Chen, M.J. Ringette, Finite-span rotating wings: Three-dimensional vortex formation and variations with aspect ratio, *Exp. Fluids* 54 (2013) 1444.
- [26] A.C. DeVoria, K. Mohseni, On the mechanism of high-incidence lift generation for steadily translating low-aspect-ratio wings, *J. Fluid Mech.* 813 (2017) 110–126.
- [27] N.H. Werner, J. Wang, H. Dong, et al., Scaling the vorticity dynamics in the leading-edge vortices of revolving wings with two directional length scales, *Phys. Fluids* 32 (2020) 121903.
- [28] L. Chen, C. Zhou, J.H. Wu, The role of effective angle of attack in hovering pitching-flapping-perturbed revolving wings at low Reynolds number, *Phys. Fluids* 32 (2020) 011906.

- [29] X.G. Meng, Ceiling effects on the aerodynamics of a flapping wing at hovering condition, *Phys. Fluids* 31 (2019) 051905.
- [30] J.D. Eldredge, A.R. Jones, Leading-edge vortices: Mechanics and modeling, *Annu. Rev. Fluid Mech.* 51 (2018) 75–104.
- [31] T. Jardin, Coriolis effect and the attachment of the leading edge vortex, *J. Fluid Mech.* 820 (2017) 312–340.
- [32] L. Chen, J. Wu, B. Cheng, Volumetric measurement and vorticity dynamics of leading-edge vortex formation on a revolving wing, *Exp. Fluids* 60 (2018) 12.
- [33] J.M. Birch, M.H. Dickinson, Spanwise flow and the attachment of the leading-edge vortex on insect wings, *Nature* 412 (2001) 729.
- [34] D. Prosser, A. Grassidis, Computational approaches to design and analysis of small-scale flapping wings, *J. Aircr.* 53 (2016) 651.
- [35] S. Chen, H. Li, S. Guo, M. Tong, B. Ji, Unsteady aerodynamic model of flexible flapping wing, *Aerosp. Sci. Technol.* 80 (2018) 354.
- [36] E. Ferrer, R.H.J. Willden, A high order discontinuous Galerkin - Fourier incompressible 3D Navier-Stokes solver with rotating sliding meshes, *J. Comput. Phys.* 231 (2012) 7037.
- [37] R. Steijl, G. Barakos, Sliding mesh algorithm for CFD analysis of helicopter rotor-fuselage aerodynamics, *Internat. J. Numer. Methods Fluids* 58 (2008) 527.
- [38] I.S. Kavvadias, E.M. Papoutsis-Kiachagias, G. Dimitrakopoulos, K.C. Giannakoglou, The continuous adjoint approach to the k- ϵ SST turbulence model with applications in shape optimization, *Eng. Optim.* 47 (2015) 1523.
- [39] X. Fan, C. Du, L. Li, S. Li, Numerical simulation on effects of film hole geometry and mass flow on vortex cooling behavior for gas turbine blade leading edge, *Appl. Therm. Eng.* 112 (2017) 472.
- [40] L. Chen, Y.L. Zhang, J.H. Wu, Study on lift enhancement of a flapping rotary wing by a bore-hole design, *P I Mech. Eng. G-J Aer.* 232 (2018) 1315.



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