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Aerodynamic Analysis of Dragonfly Wings Space Distribution On Three-Dimensional During Hovering Flight

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Abstract

Dragonfly has two pairs of wings, which are different from other single-pair-winged insects. The motion law and space distribution of dragonfly's forewing(FW) and hindwing(HW) are different in different flight states. Aerodynamic coupling between FW and HW is the key problem of dragonfly hovering flight. In this paper, we use three-dimensional numerical simulation to investigate the impact of the horizontal spacing and vertical spacing on the vertical force, horizontal force, and efficiency of the hindwing and how these changes affect the leading-edge vortex (LEV) generated by the hindwing surface. It is found that the aerodynamic interference between the forewing and the hindwing is the largest when the motion of the flapping wing reaches the maximum of upstroking and the maximum of downstroking respectively. When the vertical spacing is zero, the total vertical force of the flapping wing increases with the increase of horizontal spacing. And when horizontal spacing is 1.0x rotation axis spacing, the hindwing's lift and thrust decrease with increasing vertical spacing. The interaction between the forewing and hindwing affects the leading-edge vortex formation on the hindwing and results in changes in the aerodynamic force and efficiency of the hindwing. The result of the research shows that when the forewing is higher than the hindwing, the leading-edge vortex of the hindwing is inhibited, but it can promote the generation of the hindwing's leading-edge vortex when the forewing is lower than the hindwing. The study can be helpful for the design of dragonfly-like aircraft.

Keywords: dragonfly, CFD, tandem wings, space distribution

1. Introduction

Insects have the advantages of small size, light weight, low energy consumption and high maneuverability. They can fly forward, side and hover by flapping their wings. Different from traditional fixed-wing steady-state aerodynamics, insects flying at low Reynolds number often use unsteady-state aerodynamics to achieve maneuvering characteristics. 350 million years ago, winged insects have appeared in the world. There are millions of insects in nature, each of which has different aerodynamic characteristics and flight modes. For example, dragonfly has two pairs of wings, which can realize forward flying, hovering, side flying and inverted flying by changing the different phase difference and different space distribution between FW and HW [1]. In this paper, we will study the dynamic effects of different vertical and horizontal spacings between HW and FW.

The aerodynamic performance of dragonfly is much affected by wing's space distribution during hovering flight. Lissaman [2] proposed that fixed wing efficiency decreases at a Reynolds number below 100, 000. In the early 1970s, when studying the flight of wasps, Weis-Fogh [5] proposed that the rapid closing and opening mechanism of the wings led to the high lift force of insects at low Reynolds number.In the 1990s, people began to pay attention to the unsteady flow process of insects. In 1996, Ellington et [6] al. proposed the dynamic stall mechanism of insects to maintain the stability of high lift, and the generation and delayed shedding of leading-edge vortices (LEVs) would improve lift. Ellington pointed that insects fly in a laminar flow regime whereas most birds live in a turbulent regime. Timothy[3][4] Due to the unique independent control of four wings in tandem and the interaction between wings, dragonfly has strong body posture maintenance and adjustment ability, and can execute flexible and accurate capture process in a very limited space. In 2013, Chen et al. [7] observed the kinematics of the tied dragonfly's wings with a high-speed camera, and the wing flapping frequency was 39Hz. In 2006, Tsyuyki et al. [8] measured the dragonfly and in 1997, Wakeling et al. [9] measured the dragonfly 36Hz and 44Hz respectively. Therefore, it can be concluded that the flapping frequency of dragonfly wings ranges from 36Hz to 44Hz, and the flapping amplitude is 65±3.4°. Bomphrey R.J.[10] used the two-dimensional simulation method to verify that the horizontal spacing of dragonfly wings has a great effect on the aerodynamic performance of the hindwing and proposed that the shedding vortex of the forewing would promote the generation of the hindwing leading-edge vortex, but when the spacing was too large, it would destroy the generation of the rear wing leading vortex. Changes in spacing distribution between the hovering flapping motions of the forewing and the hindwing can affect the aerodynamic interference between the forewing and hindwing, thus affecting the efficiency of dragonfly hovering flight. In 2004, Maybury W.J.[11], by simulating the movement of two wings in tandem, concluded that downwash airflow from the front wing can delay the fall off of the LEV of the rear wing and further stabilize the lift. In 2018, Hefler C [12] pointed out that there was a wake capture process between the front and rear wings, and the leading edge vortices (LEVs) of the front and rear wings presented an obvious LEV-LEV interference mechanism, which would increase the amount of LEV loops of the rear wings, thus greatly improving lift. In 2019, Shanmugam [13] et al. used the CFD numerical simulation method to study the influence of the fore and hind distance and phase difference in the two-dimensional crosscut wing model, and found that the aerodynamic interference effect of crosscut wings was strongly dependent on the front and rear distance and phase difference.

Most of the numerical simulation of dragonfly wing spatial layout uses two-dimensional simulation method, which can not be used to observe the front and rear wings along the spanwise direction of the wake interference process. It is difficult to get a regular research results.

2. Methodology

2.1 Simulation Method

In this study, overset mesh generation technology was used to build dragonfly wings model including forewing(FW) and hindwing(HW) based on real dragonfly wing shape in Figure1. The dragonfly wing's configuration was simulated using an incompressible Navier-Stokes solver and an overlapping grid method at a Reynolds number of 4000. The grid number of outer fluid, HW fluid and FW fluid are 2.11million, 2.58 million and 2.30million respectively. We use overset mesh to avoid the difficulty of single-domain grids dealing with complex shapes and the mesh does not need to be generated again, then it overcomes the problem that the dynamic mesh is prone to negative volume. It can deal with the movement of small gaps, and the setting is more convenient and simple. Maintain good mesh quality during movement.

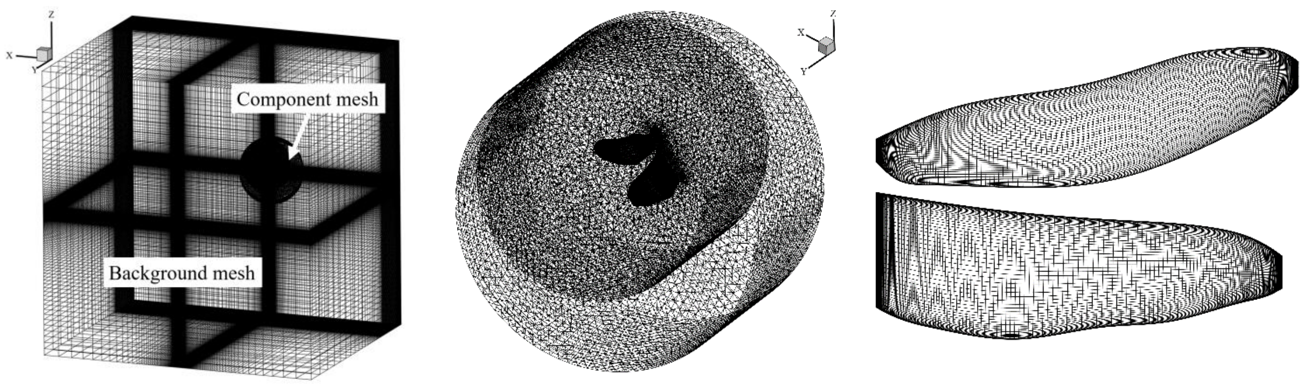
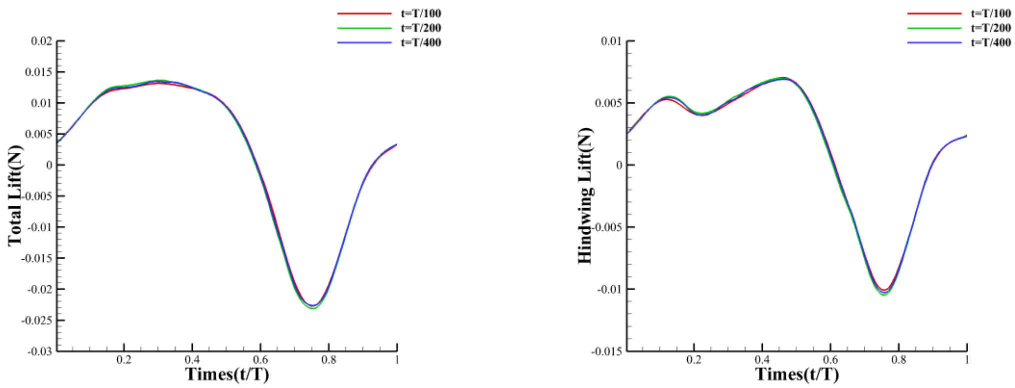


Figure 1 – The mesh of simulation.



（a）Total Vertical Force （b）Hindwing Vertical Force

Figure 2 – The Lift of Different Time Step

In the process of fluid simulation, in order to obtain the calculation results with higher accuracy, we calculated the time step as T/100, T/200 and T/400, Figure 2 shows the total vertical force acting on the dragonfly wings in the dependency study. The vertical forces of the fine and the coarse time step size systems are slightly increased and decreased, respectively. Although there is some difference between the cycle-averaged vertical force of the different time step size systems, its effect on the discussed flow features and on the aerodynamic forces is minor. The basic time step size system was adopted for this study, since the fine time step size system would be computationally more expensive.

2.2 Flapping Kinematics

In laminar flow without inflow velocity, the hovering flapping motion consists of the sinusoidal pitch, sinusoidal plunge, and sinusoidal slide motion. When the phase difference between flapping motion and sliding motion is 90°, the trajectory of dragonfly wing tip is elliptical in Figure 3, with red representing the FW and blue representing the HW. In order to explore the influence of the spatial layout of the front and rear wings on aerodynamic performance, in this study there is no relative motion between the front and rear wings, that is the phase difference is 0.

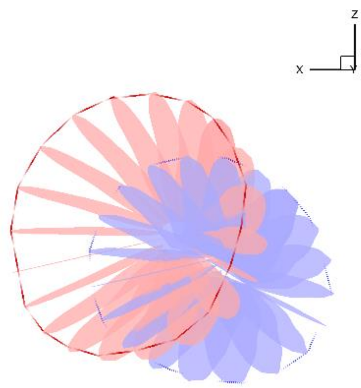


Figure 3 – Wing-tip trajectory of the FW and HW.

It is shown the motion states of the front wing in a flapping cycle in Figure 4, where blue represents the downstroke and green represents the upstroke.

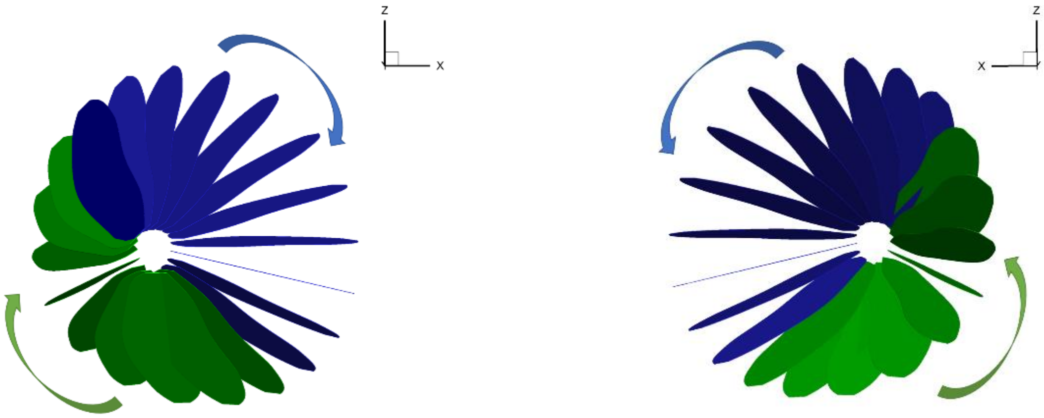


Figure 4 – The motion states of the forewing in a flapping cycle.

We built the wing motion function from the motion of the real dragonfly, where the maximum amplitude of the three degrees of freedom movement is all set to 30º.

The flapping motion of the FW and HW are represented as simple sinusoidal function given by

$$\varphi_f(t) = \varphi_m \cos(2\pi f t) \quad (1)$$

The pitching motion of the FW and HW are represented as simple sinusoidal function given by

$$\propto_f(t) = \propto_m \cos(2\pi f t) \quad (2)$$

The sliding motion of the FW and HW are represented as simple sinusoidal function given by

$$\gamma_f(t) = \gamma_m \cos(2\pi f t) \quad (3)$$

Where Ψ_m,α_m,γ_m are flapping amplitude, pitching amplitude, and sliding amplitude of FW and HW and equal 30°.

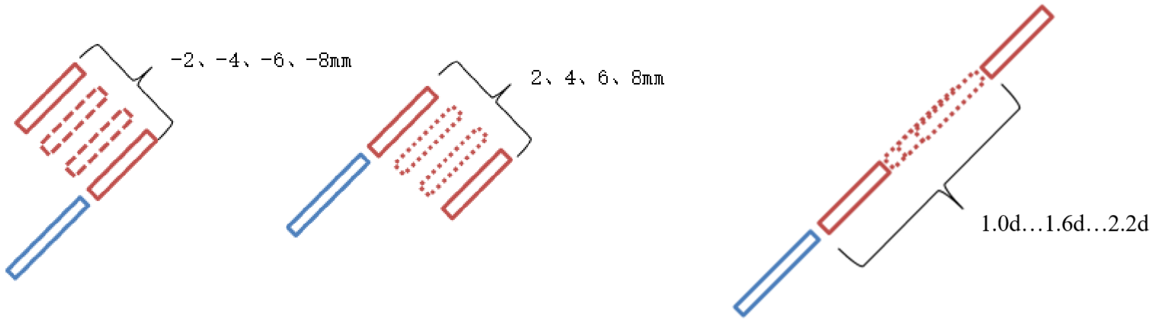
The motion function parameters of the front and rear wings of the dragonfly are shown in Table 1. Since the purpose of this paper is to study the influence of the space distribution of the FW and HW on the aerodynamic performance, the motion parameters are always consistent.

Table 1 – Hovering flight motion parameter

Hovering flight	
The flapping plane angle	45°
Pitching amplitude	30°
Sliding amplitude	30°
Flapping amplitude	30°
Phase difference between pitching and flapping	180°
Phase difference between sliding and flapping	90°

2.3 Parameters

In this study, we change six different horizontal spacings ranging from 1.0 time rotation axis spacing to 2.2 times rotation axis spacing. And we use eight different vertical spacings ranging from -8mm to 8mm were tested during hovering flight as shown in Figure.5. The initial rotation axis spacing is the real dragonfly rotation axis spacing. The vertical spacing is positive when the forewing is higher than the hindwing, and the opposite is negative.



(a) Different vertical distance (b) Different horizontal distance

Figure 5 – Different wings space distribution.

3. Results and Disscussion

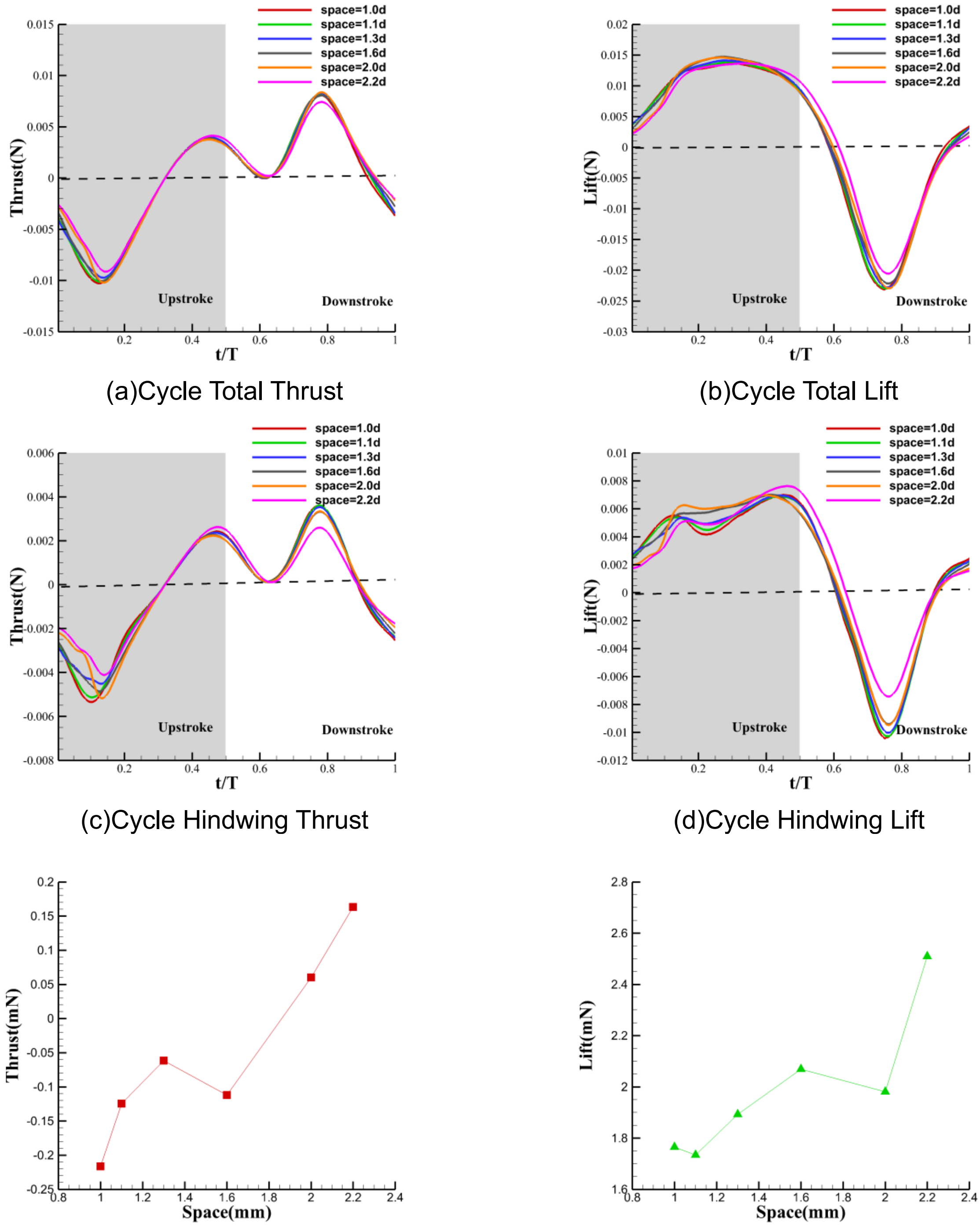
3.1 Influence of horizontal spacing

Because of the aerodynamic interference between the front and rear wings, when the vertical spacing between the FW and the HW is 0, the aerodynamic calculation results are obtained by changing the horizontal spacing between them, so as to study the effect of horizontal spacing on aerodynamic interference. The result shows that the smaller the distance between the HW and HW, the more obvious the aerodynamic interference between the FW and HW.

There are shown the total lift and total thrust which are generated by dragonfly wings during hovering flight in Figure 6(a) and Figure 6(b). According to the force graph of a flapping period, it can be concluded that changing the horizontal spacing between the front and rear wings has little effect on the overall aerodynamic force, and the effect is more significant when t=0.1. This is because when t=0.1, the FW and HW move to the top and are about to start flapping down from the top. At this point, the aerodynamic interference between the front and rear wings is obvious. The LEV generated on the front wing surface falls off and attaches to the rear wing surface, thus affecting the formation of the LEV on the rear wing surface and weakening the aerodynamic performance generated by the rear wing.

Figure 6(c) and Figure 6(d) show the thrust and lift forces generated by the rear wing in a flapping cycle. It can be seen that the change of the horizontal spacing between the FW and HW has a significant impact on the HW aerodynamics, especially at t=0.1 and t=0.75. The reason for this phenomenon is that these points are the time when the flapping transformation direction is downward and upward respectively. At this time, the LEV of the FW and the HW interfere with each other, which has a significant influence on the HW aerodynamic force.

We divide the last surrounding force of the calculation by the period time to get Cycle-averaged Force. With the increase of horizontal spacing between the FW and HW, both the total vertical force and the horizontal force increase gradually, and the aerodynamic interference between the FW and HW decreases in Figure 6(e) and Figure 6(f). When the distance between the FW and HW is 1.3d, the total horizontal force is close to 0, which is conducive to the hovering flight of the dragonfly.



(a)Cycle Total Thrust (b)Cycle Total Lift

(c)Cycle Hindwing Thrust (d)Cycle Hindwing Lift

(e)Cycle-averaged Total Thrust (f)Cycle-averaged Total Lift

Figure 6 – Total Lift, Total Thrust, HW Lift and HW Thrust at Different Horizontal Spacing.

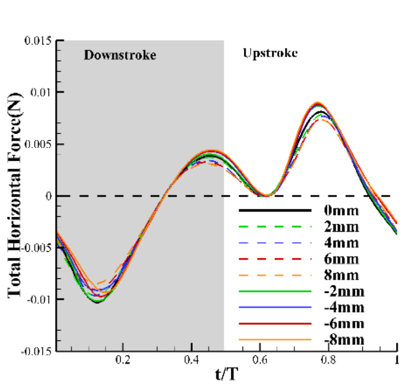
3.2 Influence of vertical spacing

Unlike the horizontal spacing, the total strength is greatly affected by the vertical spacing, especially at the peak in Figure 7(a) and 7(b). It can be seen from the periodic average total lift that when the vertical spacing of the FW is higher than that of the HW, the total thrust is almost constant and the influence of the vertical spacing is very small in Figure 7(e) and 7(f). However, the total lift has little change trend until the vertical spacing increases to 8mm and then begins to decline. When the vertical spacing of the FW is lower than that of the HW, the total thrust increases with the increase of the spacing, and is close to 0 when the spacing is -6mm. At this time, the total lift decreases slightly.

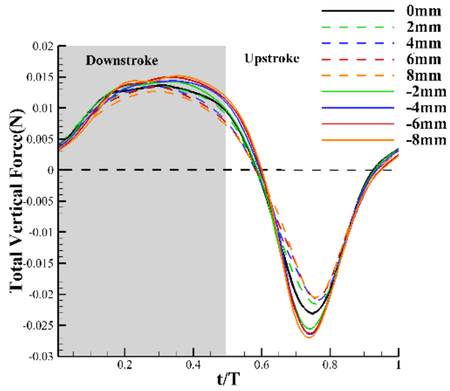
It can be seen from the Figure 7(c) and 7(d) that different vertical spacing has a great influence on the force generated by the rear wing, especially at t=0.1. When the front wing is lower than the rear wing, the thrust generated by the rear wing barely changes, while the lift gradually decreases in Figure

7(g) and 7(h). When the front wing is higher than the rear wing, the thrust generated by the rear wing gradually decreases and tends to zero, while the lift force does not change much.

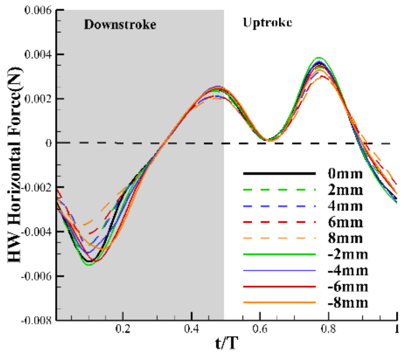
Therefore, when the dragonfly is hovering flight, it is necessary to avoid the total thrust generated by the wings and increase the total lift generated by the wings. It is more suitable to choose the vertical spacing between the FW and the HW is -6mm.



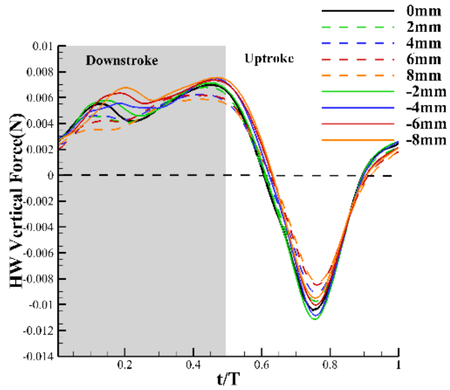
(a)Cycle Total Thrust



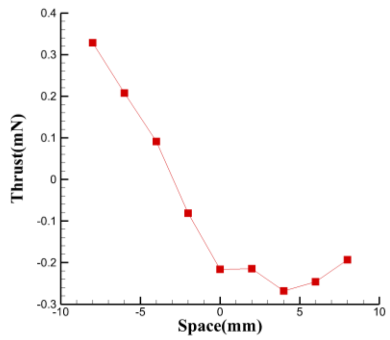
(b)Cycle Total Lift



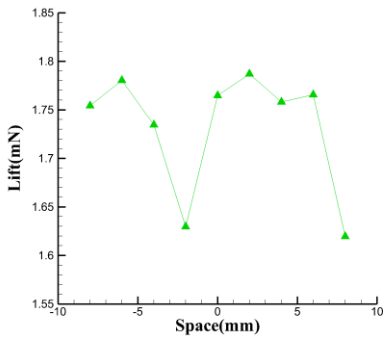
(c) Cycle Hindwing Thrust



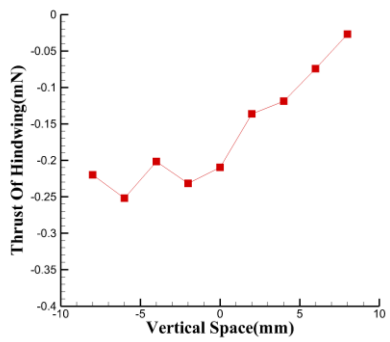
(d) Cycle Hindwing Lift



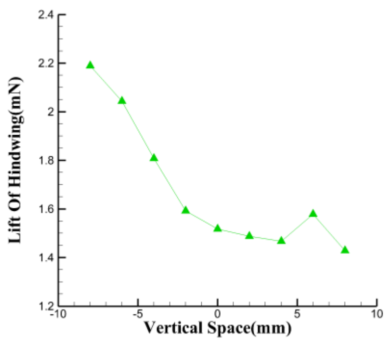
(e) Cycle-averaged Total Thrust



(f) Cycle-averaged Total Lift



(g) Cycle-averaged Hindwing Thrust



(h) Cycle-averaged Hindwing Lift

Figure 7 – Total Lift, Total Thrust, HW Lift and HW Thrust at Different Vorizontal Spacing.

3.3 Flow Field Analysis at t=0.1 with Different Vertical Space

At t=0.1, the interference between the FW and HW is obvious. The flow field at t=0.1 was used to analyze the interference mechanism of the FW and HW when the FW was higher than the HW in Figure 8, and the vorticity iso-surface was drawn with Q=40000.

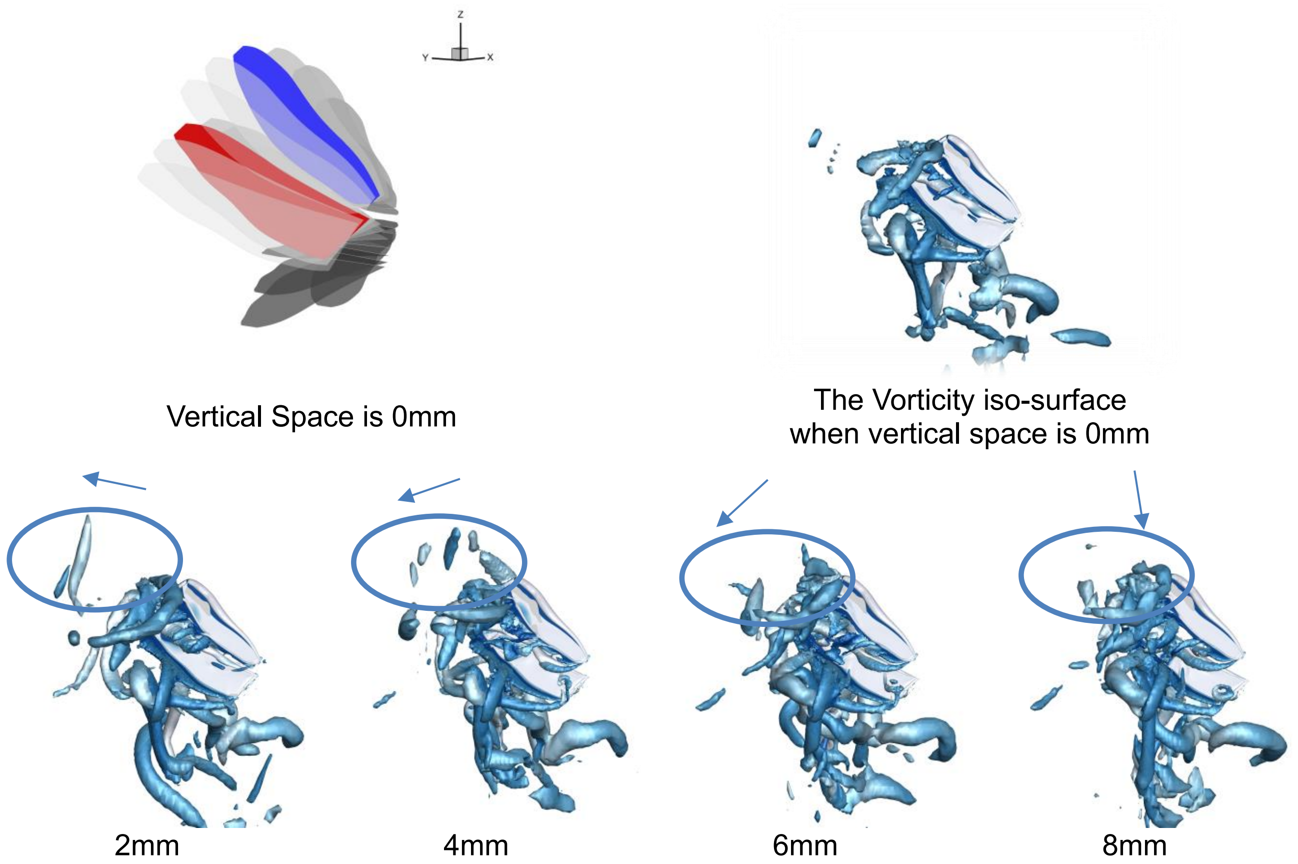
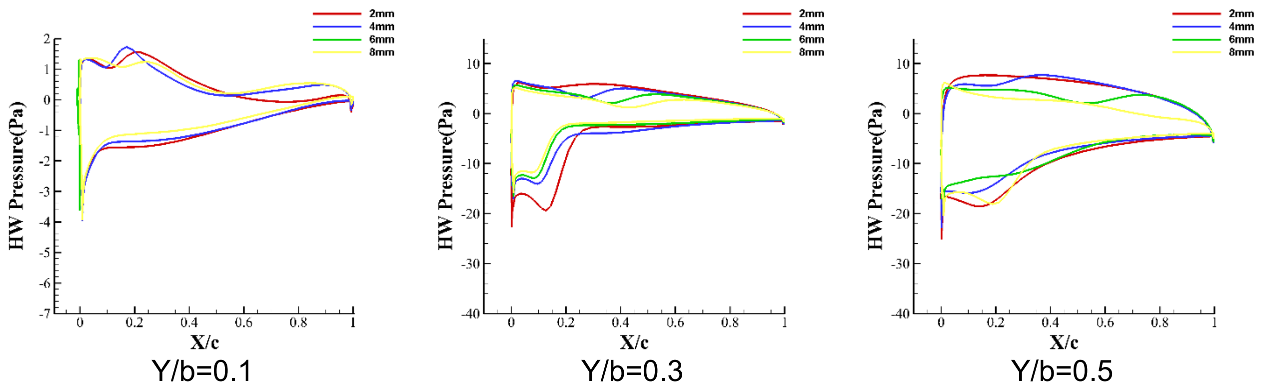
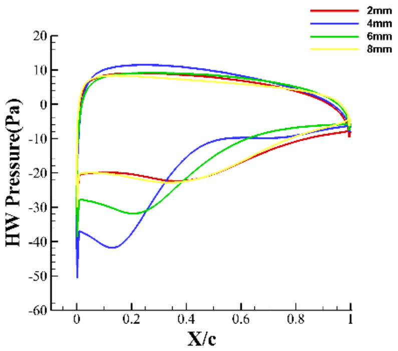


Figure 8 – The vorticity iso-surface was drawn with Q=40000 when FW is higher than HW.

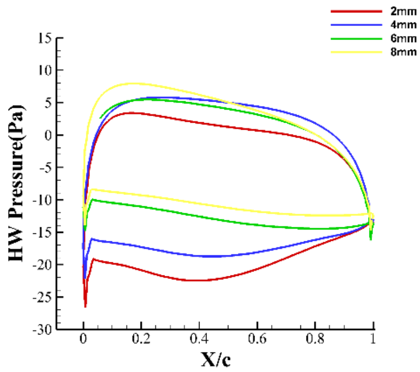
As the front wing is gradually higher than the HW, the vertical force of the HW decreases and the thrust increases in Figure 8. According to Q=40000 criterion, it is found that the vortex generated on the lower surface of the front wing at the root of the wing will fall off to the upper surface of the rear wing due to the height difference. With the increase of the height, the vortex at the front wing tip does not fall off outwards, but interferes with the HW inward, thus affecting the aerodynamic performance of the HW.

The pressure distribution on the HW surface is shown in Figure 9. It’s shown the pressure distribution of HW from the wing root to the wing tip.





Y/b=0.7

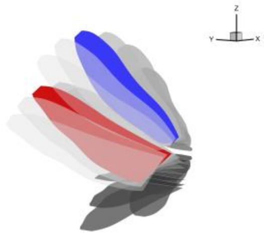


Y/b=0.9

Figure 9 – The pressure distribution form wing root to tip.

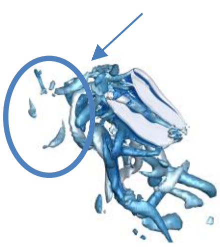
According to pressure distribution, the change of the FW and HW vertical spacing edge play a greater influence on the pressure for HW leading in Figure 9, especially at the wing root. HW on the leading edge of the surface changes significantly, with the increasing distance FW is higher than the HW, HW on the front surface of the pressure of the absolute value decreases, the pressure distribution in the area of the also decreases, This affects the generation of HW Lift.

The flow field at t=0.1s was used to analyze the interference mechanism of the FW and HW when the FW was lower than the HW in Figure 10, and the vorticity iso-surface was drawn with Q=40000.

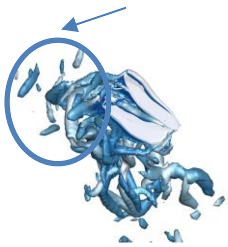


Vertical Space is 0mm

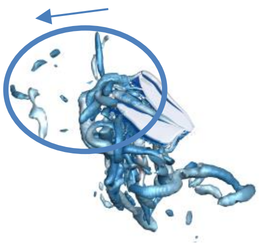
The Vorticity iso-surface when vertical space is 0mm



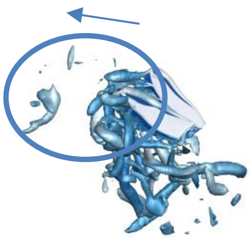
2mm



4mm



6mm



8mm

Figure 10 – The vorticity iso-surface was drawn with Q=40000 when FW is lower than HW.

When the FW is lower than the HW, the lift and thrust of the FW are greater than those of the HW when the FW is higher than the HW in Figure 10.

With the increase of the height difference between the FW and HW, the lift of the HW tends to increase.

According to Q=40000 criterion, it is found that with the increase of vertical spacings, the leading edge vortex generated on the lower surface of the FW at the root of the wing falls off to the top surface of the HW decreases, and the vortex at the tip falls off earlier, which can reduce the aerodynamic interference of the FW and HW.

Because at t=0.1, the aerodynamic force of the HW changes significantly at different vertical spacings, it’s shown that pressure distribution of HW surface in Figure 11.

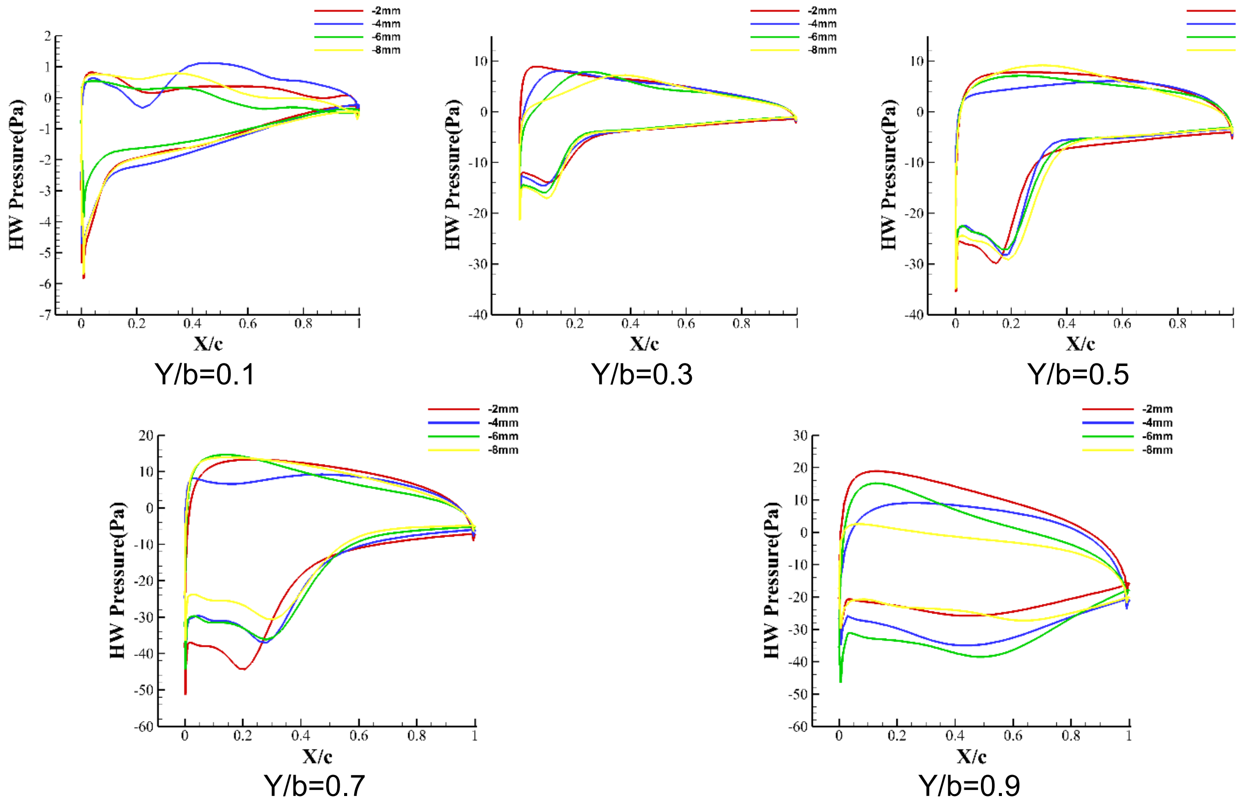


Figure 11 – The pressure distribution form wing root to tip.

The aerodynamic interference of the FW and HW at the root of the wings is obvious, and they show different law of pressure distribution respectively. As the height difference increases, the area of the pressure profile on the HW surface decreases, so the vertical force decreases gradually.

4. Conclusions

In this paper, we change the vertical and horizontal spacing of dragonfly's forewing and hindwing respectively, and get the thrust and lift forces of dragonfly performing hovering through simulation calculation.

With the increase of horizontal spacing, the aerodynamic interference between the FW and HW decreases gradually, and the total lift force increases gradually. When the FW is higher than the HW, the aerodynamic interference between dragonfly wings reaches the greatest, especially in the highest stage of upflapping, there is a strong LEV-LEV effect. The results show that when the FW is lower than the HW, the vortex of the FW promotes the generation of the HW, which increases the lift force of the HW. When the FW is 6mm lower than the HW, it is favorable for the dragonfly to hover.

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6. Acknowledgments

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7. Copyright Statement

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