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Aerodynamic Performance of Dragonfly Forewing–Hindwing Interaction in Gliding Flight

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Abstract. In order to study the aerodynamic performance of dragonfly forewing–hindwing interaction in gliding flight, the three-dimensional (3D) model with corrugation of dragonfly forewing and hindwing are established. This paper studied the aerodynamic effects of dragonfly forewing–hindwing interaction at gliding motion using the method of computational fluid dynamics (CFD) for angles of attack changing from 0° to 25° (with an interval of 5°). Numerical simulation indicates that the interactions between forewing and hindwing enhance the aerodynamic performance of both forewing and hindwing to varying degrees compared to independent wings, especially the effect of forewing is more evident at small angle of attack.

1. Introduction

The micro-flapping-wing aircraft has the characteristics of small size, light weight, excellent stealth performance and strong operability. As a brand new aircraft design structure, it can not only take off and land vertically and accelerate in almost any direction like a micro-rotor aircraft, but also can maneuver precisely at high speed and long-distance cruising like the micro-fixed-wing aircraft. Dragonfly is the most suitable bionic object for the micro-flapping-wing aircraft because of its excellent flight ability.

Gliding flight is the most commonly used flight mode of the dragonflies, especially in the summer of high temperatures. On the one hand, the aspect ratio of a single wing is about five which is much larger than other insects, and can obtain better gliding ability by consuming very little energy; On the other hand, it can reduce the flapping frequency and energy consumption, and regulate body temperature by using the methods such as air convection[1]. Unlike other four-winged insects, dragonfly forewing and hindwing are independent and mutually influential. It is interest that dragonfly could spread a pair of hindwing but flapping a pair of forewing, or spread all wings stationary in gliding flight[2].

Due to the advances in CFD and experimental techniques, researchers are beginning to study the aerodynamic performance of the dragonfly wings. However, there are few studies about the aerodynamic performance of forewing–hindwing interaction in gliding flight. Sun and Lan[3] & Wang and Sun[4] studied the aerodynamic performance of forewing–hindwing interaction in hover flight and forward flight, using the method of CFD. Maybury and Lehmann[5] & Yamamoto and Isogai[6] conducted experimental studies on the forewing–hindwing interaction at hovering conditions. Zhang and Lu[7] studied the aerodynamic performance due to forewing and hindwing interaction with two-dimensional (2D) model of dragonfly wings in gliding flight. Huang and Sun[8]



studied the aerodynamic performance of the dragonfly forewing–hindwing interactions by using 3D model wings, which are simplified to a flat model only with the outer contour of the dragonfly wings for both forewing and hindwing.

In fact, the structure of the dragonfly wings is very complicated. Although it seems to be a 2D planar structure, it is actually a complex 3D spatial structure with corrugation. Therefore, it is desirable to study the forewing–hindwing interaction by using 3D model with corrugation of the dragonfly forewing and hindwing.

In order to study the aerodynamic performance of dragonfly forewing–hindwing interaction in gliding flight, the 3D model with corrugation of the dragonfly forewing and hindwing are established. This paper studied aerodynamic effects of dragonfly forewing–hindwing interaction at gliding motion using the method of CFD for angles of attack changing from 0° to 25°(with an interval of 5°).

2. Numerical Method

2.1. Governing Equations

The 3D incompressible Navier-Stokes equations are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{\text{Re}} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{\text{Re}} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (3)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{\text{Re}} \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (4)$$

where p and t is the pressure and time, and u,v,w are the components of the velocity along the x,y,z directions, and Re corresponds to the Reynolds number.

Lift coefficient and drag coefficient are the main basis for judging the aerodynamic performance, which are defined as:

$$Cl = \frac{F_l}{0.5\rho U^2 c} \quad (5)$$

$$Cd = \frac{F_d}{0.5\rho U^2 c} \quad (6)$$

where ρ , U and c are the density, velocity of the free stream and the average chord length of dragonfly wings, respectively, F_l and F_d are the lift and drag.

2.2. Geometric models

Dragonfly wings is mainly composed of thin cuticular membrane and veins. Veins can be divided into longitudinal veins and transverse veins, and the thickness of membrane is only 0.04 mm, moreover, the shape of the cross-section of the wing is pleated along the extension, and the thickness of the entire cross-section is also slightly different[9].

According to the characteristics of real dragonfly wings and the actual measured data by Okamoto[9], this paper have built the 3D model with corrugation of the dragonfly forewing and hindwing by using the 3D modeling software through reverse engineering. In order to simplify the model realistically, this paper ignored impact of the extremely tiny corrugations and some structures like pterostigma, nodus etc. In addition, the thickness of the cuticular membrane and veins, as well as the shape of the vein, are simplified to be consistent throughout the dragonfly wings[10].

Figure.1 shows the 3D model of dragonfly forewing and hindwing, respectively, Figure.1(a) is the 3D model of dragonfly forewing(where 1-5 is the corrugation structure of the dragonfly forewing to different positions), Figure.1(b) is the 3D model of dragonfly hindwing (where a-d is the corrugation

structure of the dragonfly hindwing to different positions), and Figure.1(c) is the schematic diagram of wing membrane (where 1 is veins, 2 is cuticular membrane and 3 is the support structure composed of veins).

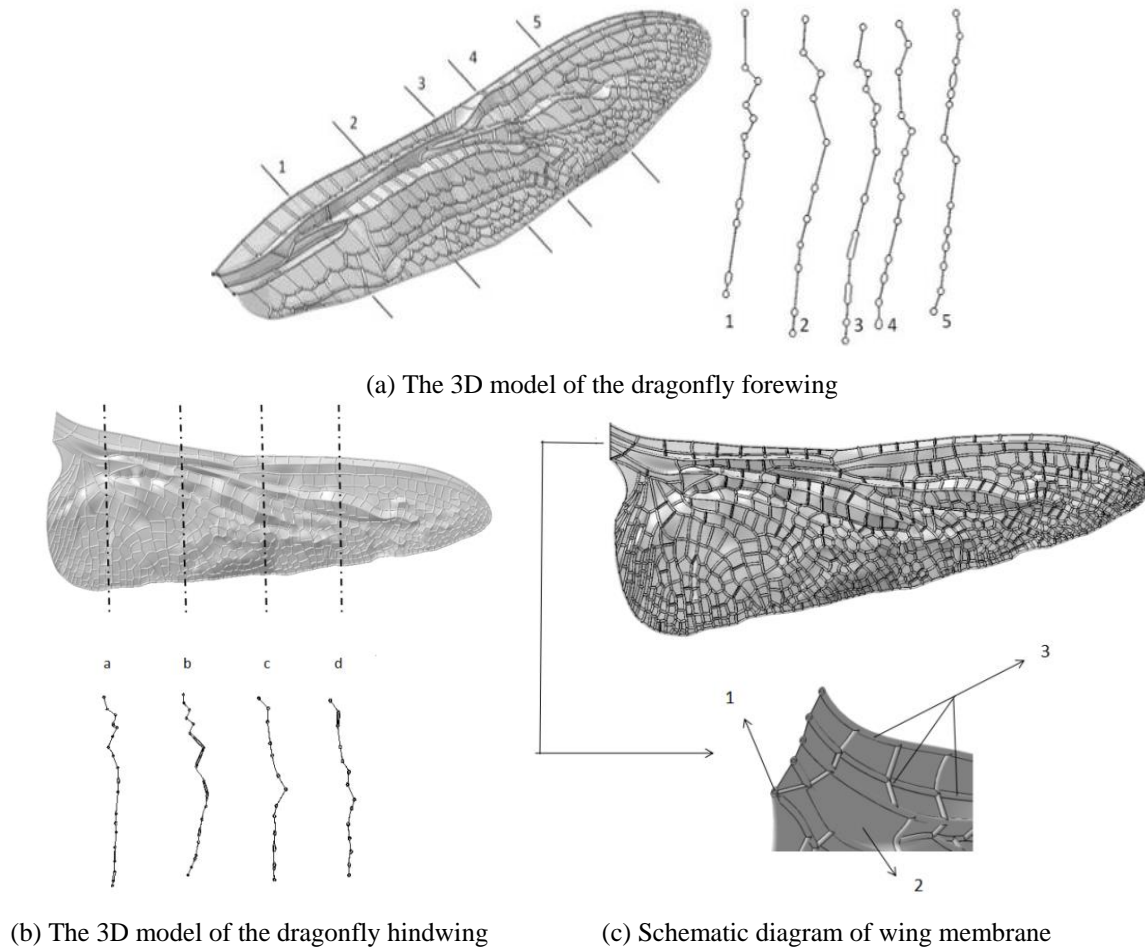


Figure 1. The 3D model of the dragonfly wings

2.3. Boundary Conditions

As shown in Figure 2, the computational domain is composed of cuboids with length, width and height of $15L$, $10L$ and $10L$ respectively (where L is the length of the hindwing). The boundary conditions of left field and the dragonfly wings are symmetry and wall respectively.

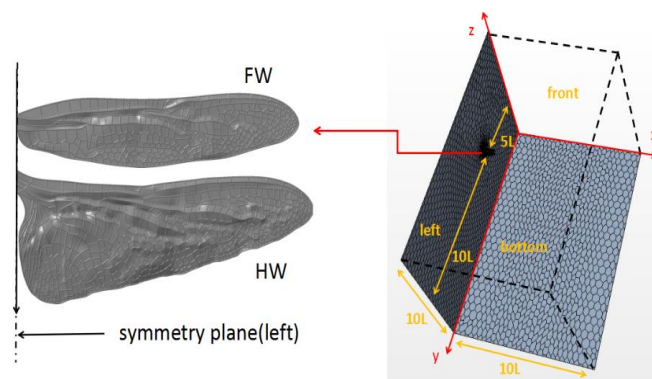


Figure 2. Computational domains

2.4 Grid Independence Verification

In order to eliminate the influence of grid size on the results, several different sizes mesh models of the dragonfly forewing and hindwing were calculated at gliding motion independently in the case of $\alpha = 0^\circ$, $V = 4.5$ m/s.

The results show that when the grid sizes are 0.03mm, 0.04mm and 0.05mm, respectively, the lift coefficients of forewing are 0.119, 0.123, 0.129, and the lift coefficients of hindwing are 0.131, 0.134, 0.139. When the grid size is 0.04mm, the relative tolerance of two single wing are both less than 5%, so it can be considered that the result is independent of the grid size. Considering the balance between accuracy and efficiency of the numerical simulation, the mesh model with grid size of 0.04mm is selected as the solution model.

3. Results and Discussion

The flow fields around the aerodynamic effects of dragonfly forewing–hindwing interaction at gliding motion are simulated for $V = 4.5$ m/s and angles of attack changing from 0° to 25° (with an interval of 5°). To obtain quantitative data on the interactions between the forewing and hindwing, flows around independent forewing and hindwing that has the same condition are also computed.

The force coefficient of dragonfly forewing and hindwing obtained from numerical simulation are shown in Figure.3, where (a),(b) and (c) is the lift coefficient, drag coefficient and lift-drag ratio respectively.

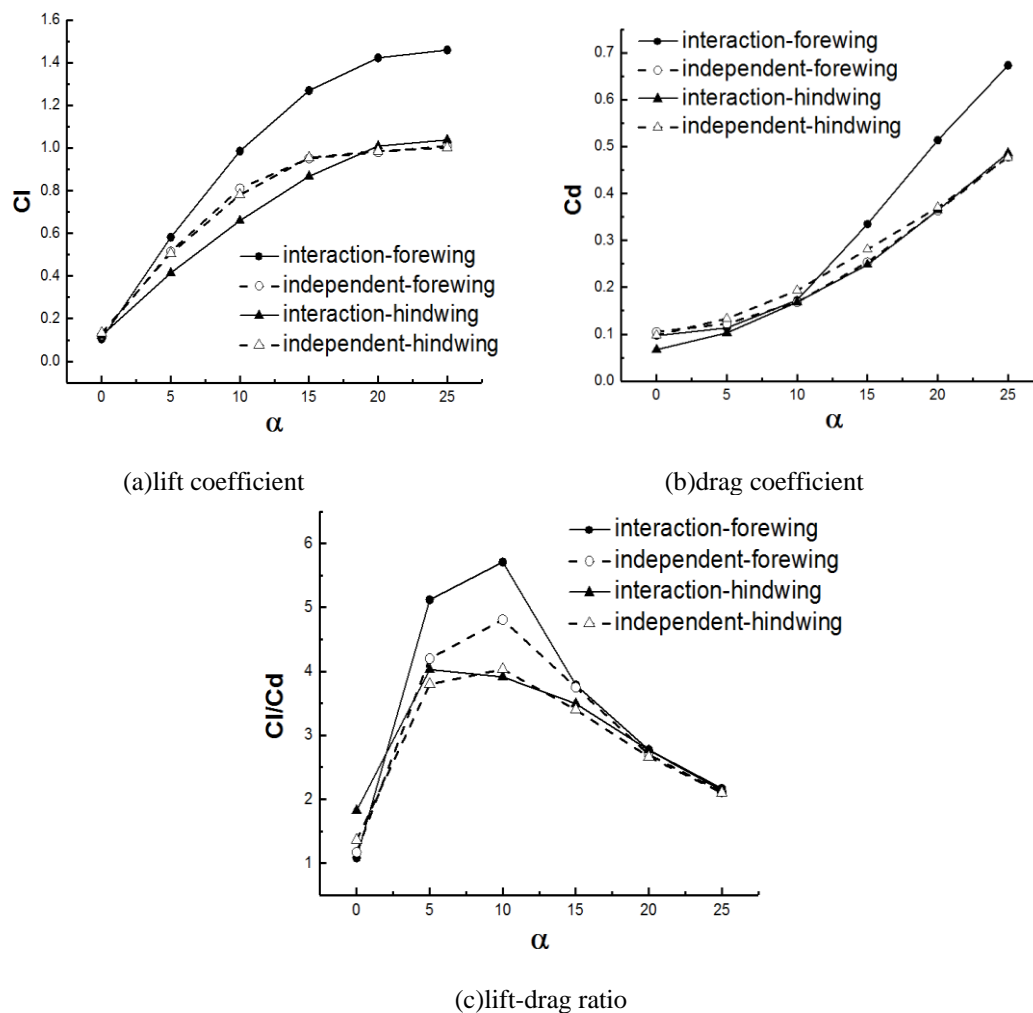


Figure 3. Force coefficient of forewing and hindwing

Only consider the case when the forewing and hindwing are gliding independently, the results are as follows: (1) The growth trend of both wing's lift and drag coefficient is consistent; (2) The lift coefficient of the independent forewing and independent hindwing is almost equal over the entire range of parameters tested, however the drag coefficient of hindwing is slightly larger than forewing when the angles of attack changing from 5° to 20° ; (3) The aerodynamic performance of forewing is slightly better than hindwing, especially at small angle of attack.

To further understand the dragonfly forewing–hindwing interaction, the force coefficient in different conditions were compared. As shown in Figure.2, (1) The forewing–hindwing interaction increase the lift coefficient of forewing significantly, and the growth rate is -17.1% 、 11.4% 、 17.7% 、 25.0% 、 31.1% 、 30.7% compared to single forewing for angles of attack changing from 0° to 25° (with an interval of 5°); In the case of the smaller angle of attack, the drag coefficient of forewing is similar in both cases. However, it is evident larger than that of single forewing at larger angle of attack; (2) The forewing–hindwing interaction decrease both lift and drag coefficient of the hindwing to varying degrees almost over the entire range of parameters tested; (3) Compared to independent wings, the forewing–hindwing interaction enhances the aerodynamic performance of both forewing and hindwing to varying degrees, especially the effect of forewing is much more evident at small angle of attack.

Figure.4 shows the pressure contours of forewing–hindwing interaction at different angles of attack with profile cross sections shown below at $0.2L$, in which the blue area represents the negative pressure, and the red or yellow areas represent the positive pressure. As shown in Figure.4, the magnitude and range of negative pressure on the upper surface and positive pressure on the lower surface of both forewing and hindwing are obviously enhanced with the increase of the angle of attack, especially the pressure changes on the upper and lower surfaces of forewing are significantly stronger than hindwing.

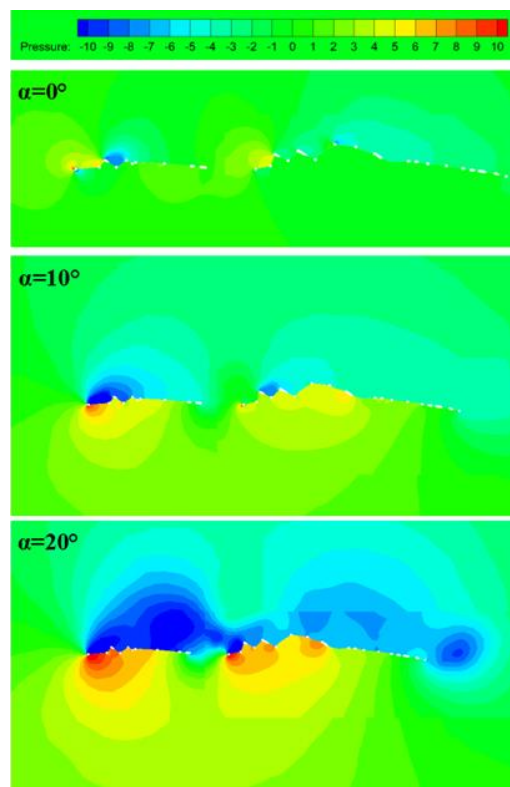


Figure 4. Pressure contours of forewing–hindwing interaction for different angles of attack with profile cross sections shown below at $0.2L$

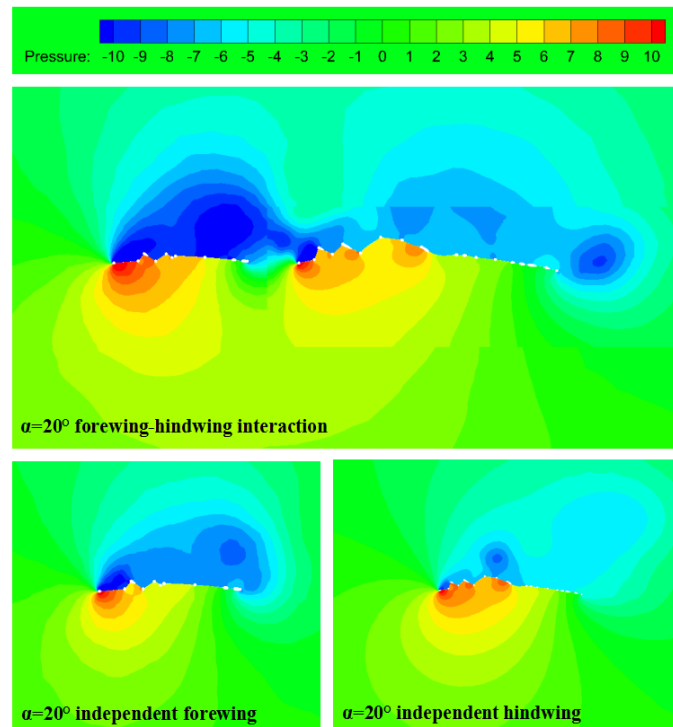


Figure 5. Pressure contours of dragonfly wings at angle of attack 20° shown below at $0.2L$

Figure 5 shows the pressure contours of dragonfly wings in two different situations at angle of attack 20° . As shown in Figure 5, the forewing–hindwing interaction significantly enhance the magnitude and range of forewing’s negative pressure on the upper surface and positive pressure on the lower surface compared to independent forewing; The positive pressure of the lower surface of the hindwing is not much different from independent hindwing, but the negative pressure on the upper surface is slightly larger.

Figure.6 shows the streamline of dragonfly hindwing in two different situations at angles of attack 10° and 20° . As shown in Figure 6, there is a trapped vortex inside each corrugation which rotates clockwise on the upper surface and counterclockwise on the lower surface, and it gradually moves out of the fold with the increase of the angle of attack. For the hindwing, the interactions only delayed the vortex shedding at large angle of attack, but had little effect on the aerodynamic performance of hindwing.

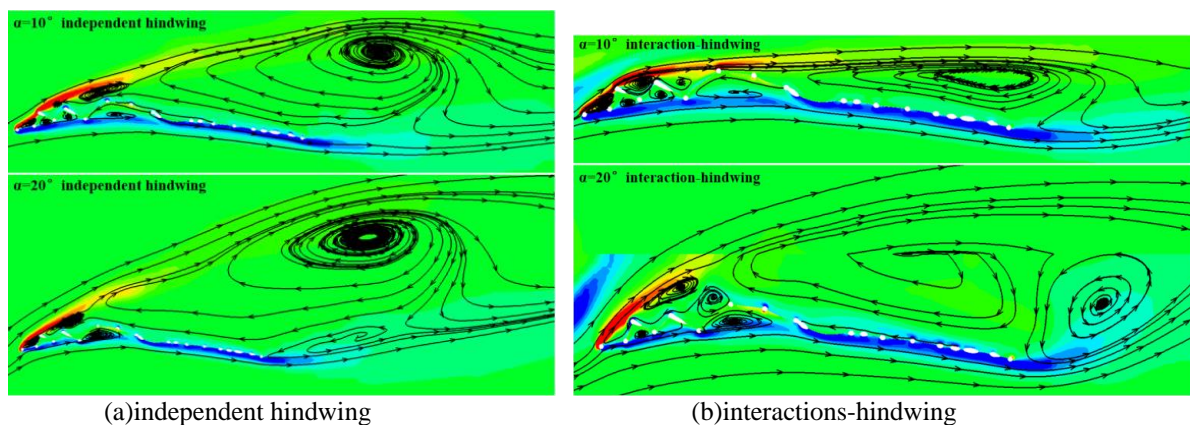


Figure 6. The streamline of dragonfly hindwing in two different situations at angle of attack 10° and 20° with profile cross sections shown below at $0.2L$

4. Conclusion

As the most suitable bionic object for the micro-flapping-wing aircraft, Dragonfly wings has always been a hot research topic. Numerical simulation indicates that the interactions between forewing and hindwing enhance the aerodynamic performance of both forewing and hindwing to varying degrees compared to independent wings, especially the effect of forewing is much more evident at small angle of attack.

The establishment process of 3D model of dragonfly wings can provide potential inspiration for other bionic calculation research. The results of the numerical simulation can also provide some reference for the design of bionic micro-flapping wing aircraft with different requirements.

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