Numerical Study on the Aerodynamic Performance of the Rigid and Corrugated Forewing of Dragonfly in Flapping Flight

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Abstract. The dragonfly flapping flight as a kind of important flight model, in order to explore the aerodynamic effect on the forewing of dragonfly in flapping. Based on the real dragonfly wings (with corrugation 3D forewing), this paper uses X-flow software numerical simulation for the model, analyzed the influence of different flow velocity and frequency on the aerodynamic effect of the forewing of dragonfly. When the dragonfly flies forward stably, the results show that it has a higher lift with the increase of inflow velocity and flapping frequency. The leading edge vortex (LEV) of the dragonfly's forewing does not fall off in a flapping period, and the maximum positive lift is generated in the downstroke. When the trailing edge vortex is strong, the peak value of thrust coefficient appears in the process of flapping, and the energy of the trailing edge vortex may provide the thrust for the dragonfly forward flight.

1. Introduction

Dragonflies, as the most capable fliers in nature, exhibit a variety of flight modes, including glide flight, flapping wing forward flight, tandem flight, low-speed maneuver and hovering, and they have been recorded to fly at speeds of up to 10m/s[1,2]. The excellent flying ability of dragonflies mainly comes from the ingenious structure of wings and a variety of flapping ways[3]. The dragonfly has high mobility, good controllability and low noise level, which makes it an ideal choice for bionic micro air vehicles (MAVs), so it has important application value in military investigation, search and rescue[5].

At present, there are many researches on the aerodynamic characteristics of dragonfly wings around the world. Kesel's analysis of dragonflies cross-section folds shows that folds can improve the lift of dragonflies wings[6]. Sun and Lan demonstrated that the interaction between the forewing and hindwing can reduce the vertical force compared to the single moving wing[7].

The model in this paper refers to the model built by Liu. According to the actual structural characteristics of dragonfly's forewing and the measurement of dragonfly's forewing, ignoring the extremely small corrugated and the influence of corrugated internal structure, as well as the slight change of wing vein shape, and simplifying the wing vein shape of dragonfly's forewing into a circular tube, as shown in figure 1. X-Flow software was used to simulate the model numerically in the case of unsteady flow field with low Reynolds number. Solving the flow field characteristics around the forewing of dragonflies. Analyze the impact of flapping frequency and inflow velocity on the aerodynamic efficiency of dragonfly flapping. I hope to
provide necessary theoretical and technical support for the development and improvement of the flapping aircraft.

2. Physical models and numerical methods

2.1. Flapping model
In order to conveniently show the position of the forewing in space and the flapping parameters of the forewing when the dragonfly flapping, the forewing of the dragonfly is assembled on the body of the dragonfly, as shown in Figure 2. But for reasons of simplified numerical simulation, this paper ignores the dragonfly body and the influence of the hindwing on the aerodynamic efficiency of the forewing, only numerical simulation of corrugated forewing of dragonfly. When the flapping wing of dragonfly forward flight, the forewing is doing complex space movement, which can be simplified as the overlapping of two parts of flapping up and down around the body axis (z axis) and twisting around the wing span direction (x axis).

2.2. Flapping equation
The equation of flapping Angle $\alpha$ of dragonfly's forewing changing with time $t$ is

$$\phi = \phi_0 + A \cos(2\pi ft - \theta_0)$$

(1)

The equation of torsion Angle $\alpha$ of dragonfly forewing changing with time $t$ is

$$\rho = \rho_0 + \sum_{n=1}^{3} B_n \cos(2\pi ft + \theta_n)$$

(2)

2.3. Setting Project
In order to study the influence of different inlet velocity and frequency on the flow field and aerodynamic force around the forewing of dragonfly, this paper carried out numerical analysis on the three-dimensional corrugated forewing model of dragonfly's with 5 groups of different inlet velocity and 5 groups of different frequencies. According to Wang's measurement, the default forward flight speed is 1.71 m/s, and the frequency is 33.4 Hz.

3. Numerical simulation and Result analysis

3.1. Influence of inlet velocity on aerodynamic characteristics of flapping wing
Fig 3 and Fig 4 show the curves of lift coefficients and drag coefficients with time in one cycle. It can be seen from the figure that the curves of lift coefficient and drag coefficient change the same trend at different speeds. At the beginning, the forewing of dragonfly upstroke from the lowest point. When forewing upstroke, the lift coefficient is negative; when forewing downstroke, the lift coefficient is positive. The maximum value of negative lift is generated in the upstroke, and the maximum value of positive lift is generated in the downstroke. The value of lift coefficient decreases with the increase of velocity. When the
speed is small, there will be drag at the beginning of flapping. When the velocity is greater than or equal to 5m/s, the whole flapping period of the forewing is almost negative, that is, the thrust is generated, and the higher the velocity, the smaller the thrust is generated. In a flapping cycle, the thrust produces two peaks, one in the upstroke and one in the downstroke, among which the thrust peak generated in the downstroke is about 2 times of the upstroke.

![Figure 3. Curve of lift coefficient with time in a cycle](image1)

![Figure 4. Curve of drag coefficient with time in a cycle](image2)

Figure 5 shows the pressure distribution on the upper and lower surfaces of the forewing at different times when the velocity is 5m/s. In the initial position, the forewing of the dragonfly starts to upstroke from the lowest point, and the pressure difference between upper and lower surfaces gradually increases. When it reaches 0.25T, the dragonfly upstroke the horizontal position, the pressure on the upper surface is significantly higher than that on the lower surface. The pressure difference between the upper and lower surfaces reaches the maximum, generating the maximum negative lift, which corresponds to the trough value of the lift coefficient curve (in Figure 3). When the forewing continues to upstroke to the highest point (0.5T), the differential pressure between the upper and lower surfaces is almost zero, and the drag coefficient generated is almost zero. After reaching the highest point, the forewing of the dragonfly starts to downstroke. During the downstroke, the flapping speed increases and the pressure difference between the upper and lower surfaces gradually increases. At 0.75T, a low pressure area is formed on the upper surface and a high pressure area is formed on the lower surface. The pressure difference between the upper and lower surfaces reaches the maximum, generating the maximum positive lift, which corresponds to the peak value of the lift coefficient curve (Figure 3). As the wing tilts forward at this time, the thrust coefficient also reaches the peak value (Figure 4).

![Figure 5. Upper and lower surface pressure cloud(v=5m/s)](image3)
When \( t = 0.25T \), the forewing of dragonfly begin to upstroke from the lowest point, the vorticity mainly appears in the lower wing surface, and also produces a large trailing edge vortex. At this time, the maximum negative lift and the first thrust peak appear corresponding to figure 3 and figure 4. Then, the forewing continues to upstroke. When \( t = 0.5T \), the forewing upstroke to the highest point, at this time, the trailing edge vortex is very small and the thrust coefficient is almost zero. Next, the downstroke starts from the highest point. When \( t = 0.75T \), vorticity appears on the upper wing surface and generates strong trailing edge vortex. At this time, the maximum value of positive lift coefficient and the peak value of thrust coefficient appear for the second time (corresponding to figure 3 and figure 4). The lift coefficient \( C_L \) and drag coefficient \( C_D \) in the flapping of dragonfly come from the non-stall mechanism (leading edge vortex does not fall off), and the generation of trailing edge vortex provides thrust for the flapping of dragonfly.

### 3.2. Influence of frequency on the aerodynamic characteristics of flapping

As can be seen from figure 7 and figure 8, with the increase of frequency, the variation trend of lift coefficient and drag coefficient is the same. With the frequency increases, the corresponding values of wave crest and wave trough of lift coefficient are increasing, that is, the positive lift in the downstroke and the negative lift in the upstroke both increase. When the frequency is small, resistance will be generated in the upstroke at the beginning. When the frequency is greater than or equal to 33.4Hz, thrust will be generated in the whole cycle. The higher the frequency is, the greater the thrust will be. The thrust peak generated in the downstroke process is twice as much as that in the upstroke.

### 4. Conclusion

In this paper, the aerodynamic performance of the flapping of the corrugated forewing of dragonfly is analyzed, and a three-dimensional model of "flapping-twisting" is established. By using the computational fluid dynamics software x-flow, the influence of flapping frequency and inflow velocity on flapping wing lift coefficient and drag coefficient was studied. Some laws of aerodynamic characteristics of corrugated forewing during flapping were obtained.
By increasing the flapping frequency and inlet velocity of the forewing, the lift coefficient can be improved. During a flapping period, the leading edge vortex (LEV) does not fall off, which is the main reason for the high lift mechanism. During the upstroke and downstroke, a thrust peak is generated at the strong trailing edge vortex, and the energy of the trailing edge vortex may provide the thrust during the forward flight.

5. Reference

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