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Numerical Simulation on Aerodynamic Characteristics of Bionic Corrugated Flapping Wing

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Abstract

Dragonflies are small in size, but extremely flexible. For example, dragonflies can easily hover, fly forward, or even fly backward. Meanwhile, the tandem corrugated flapping-wing sections, which is a very unique characteristic of dragonflies, is also the focus domain of researchers. This paper is devoted to finding the advantages of dragonflies' corrugated wing section via numerical simulation and provides a new perspective of Micro Aerial Vehicles' (MAVs) design. Dragonflies' corrugated wing section is sparkle for MAVs design. This paper is modeling 2D mid-span airfoil and focusing on how different dynamic parameters and different flapping motions can affect corrugated wing aerodynamics.

Keywords: tandem corrugated wing, CFD, aerodynamic characteristics, bionic

1. Introduction

Nature always guides mankind to learn how to achieve flying. From big birds like Albatrosses to as small as insects, they all have charming characteristics which can inspire human. With the development of Micro Aerial Vehicles (MAVs), figuring out what the mechanisms of insects flying is vital for MAVs design.

Dragonflies are a kind of unique insect. They have a small size with extremely flexible mobility. In a certain condition, they can easily hover, fly forward, or even fly backward. Another special part of dragonflies is the tandem corrugated flapping-wing sections, which is very different from other insects. These reasons attract scientists and make them focus on this outstanding creature.

In 1975, Norberg used steady aerodynamics to calculate dragonflies' lift [1], noticing the lift which dragonflies generate in steady cannot balance the weight. Further, he realized non-steady aerodynamics is key to solve that and concluded that 60% of dragonflies' lift comes for non-steady aerodynamics. Then Savage used visualization experiments to explore 2D dragonflies' airfoil [2]. He found that the non-steady condition influences hovering performance. In 1984, scientists began to focus on the tandem corrugated wing sections. Alexander noticed that in the wind tunnel experiment, the motion of the fore wing and the hind wing is not synchronized [3]. The result showed that there has a phase difference between the two wings. Kesel took a deep look at the dragonflies' airfoil and fond that the wing is not flat but full of corrugation [4]. After researching, Kesel believed that the corrugation leads to the vortex generation and provides lift to dragonflies. With the development of numerical simulation, more and more researches about dragonflies' aerodynamics characteristics have done.

This paper is standing on the basis of the forerunner, using numerical simulation to calculate the 2D corrugated flapping-wing sections. Modeling and calculating the mid-span sections by setting multiple phase difference and flapping frequency to illustrate the aerodynamic characteristics and explore the suitable flapping condition for MAVs.

2. Models and Methods

The certain species of dragonflies that this paper chose is Anax Julius. It is one of the largest dragonflies in the world and widely inhabits. The average airspeed for Anax Julius is 10m/s.

Figure 1 – Dragonfly Anax Julius.

The chord length in the middle wing sections is 8.1mm and 9.3mm for the fore wing and hind wing [5,6].

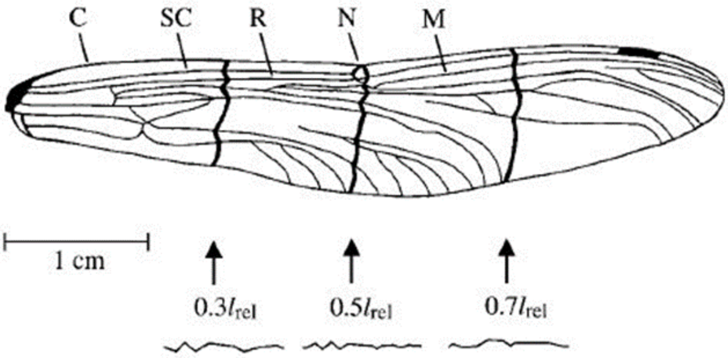


Figure 2 – Anax Julius' fore wing.

For MAV design, enlarging wings 10 sizes and rebuilding the mid-span airfoil through modeling software (CATIA V5) as shown in Figure 3, more details as follows.

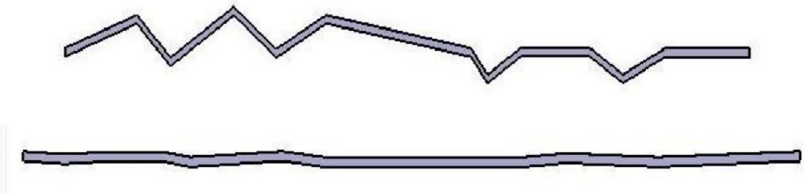


Figure 2 – Anax Julius' midsections airfoils (up fore wing).

Table 1 – Parameters of the model.

Position	Chord length	Thickness
Fore wing	81mm	1mm
Hind wing	93mm	1mm

The movement of the wing section can be summarized by Broering's research [7] as equation (1), (2).

$$\alpha(t) = \alpha_0 \, cos(2\pi f t + \phi_\alpha + \phi_h) + \alpha_{ave} \quad (1)$$

$$h(t) = h_0 cos\,(2\pi f t + \phi_h) \quad (2)$$

Further, Qiushi Li finds that while the dragonfly is taking off, it will change its body position to more vertical [8] as shown in Figure 3.

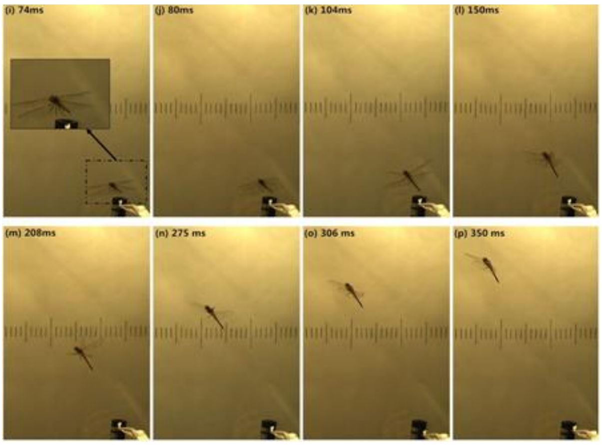


Figure 3 – Body position changes during takeoff.

The equation of motion will be expended to 3DOF (pitching, heaving, moving).

$$x_f(t) = \frac{A_f}{2}\cos(2\pi f)\, cos\beta_f \quad (3)$$

$$y_f(t) = \frac{A_f}{2}\cos(2\pi f)\, sin\beta_f \quad (4)$$

$$\alpha_f(t) = \alpha_0 \cos(2\pi f t + \phi_\alpha + \phi_h) + \alpha_{ave} \quad (5)$$

$$x_h(t) = \frac{A_h}{2}\cos(2\pi f)\, cos\beta_h \quad (6)$$

$$y_h(t) = \frac{A_h}{2}\cos(2\pi f)\, sin\beta_h \quad (7)$$

$$\alpha_h(t) = \alpha_0 \cos(2\pi f t + \phi_\alpha + \phi_h) + \alpha_{ave} \quad (8)$$

In the above equations, $\alpha(t)$ represents pitching angel, α_0 controls the angle’s range and α_{ave} is the average angle of attack (AOA). Same, $h(t)$ and h_0 represents heaving distance and a half range. f in cosine function means frequency. ϕ_α and ϕ_h are pitching phase and heaving phase. The letters f and h are the first letters from the fore wing and hind wing.

Since this paper is using numerical simulation to research corrugated wing sections, the computing method is vital for this study. The computational domain will be divided into 3 parts as shown in Figure 4.

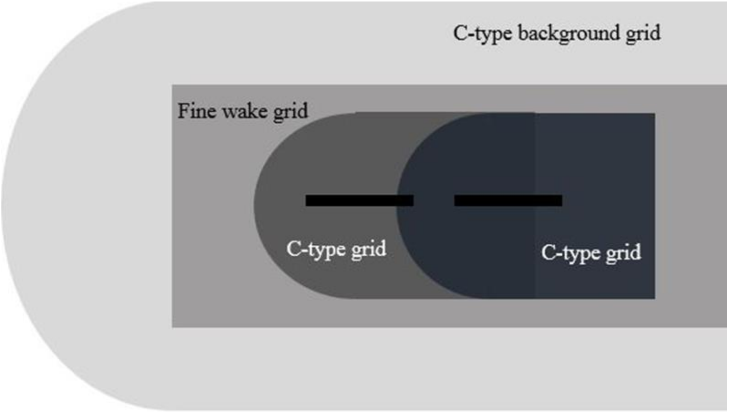


Figure 4 –Overset grids for calculation (not shown to scale).

The entire computational domain is 20 times chord length. After grids generation, the total grids number is 170,743, the specific fore wing section has 76,344 and the hind wing section has 75,516. Use the User Defined Function (UDF) to control model movements and Fluent to solve the case.

3. Calculation and Results

3.1 Case Verification

Before starting to calculate, the computational method needs to be verified in case of error. This paper chose 2D flat flapping motion which introduced by Broreing [7] as shown in Figure 5.

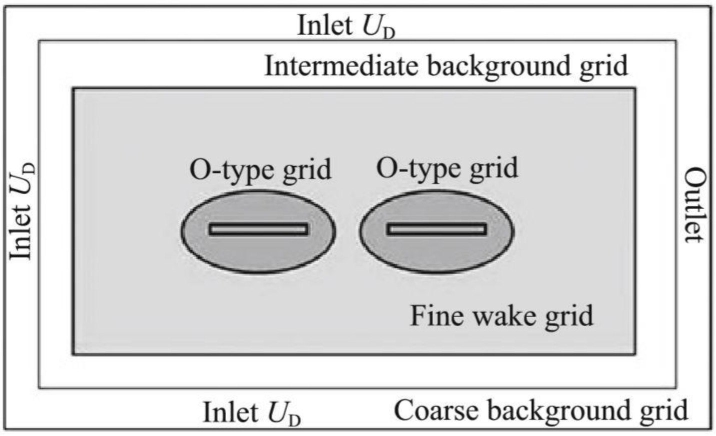


Figure 5 –Simple for Broreing’s case.

After calculation, the result is showing in Figure 6. Two results show barely difference while comparing, so the method which is used in this paper can ensure the following study.

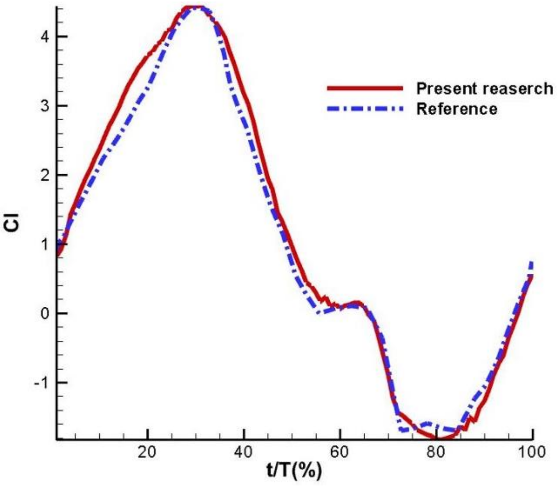


Figure 6 –Result comparison.

3.2 Lift and Thrust in Different Frequency

The frequency which dragonflies chose is vital for aerodynamic characteristics. This paper first focuses on the influence caused by a different frequency. The motion parameters are shown in Table 2.

Table 2 – Motion parameters.

Parameters	Fore wing	Hind wing
$\alpha_0/(°)$	20	20
f/Hz	1/2/3/5/8/10	1/2/3/5/8/10
$\phi_\alpha/(°)$	90	90
$\alpha_{ave}/(°)$	0	0
h_0/c	0.5	0.5
$\phi_h/(°)$	0	0

The peak of lift coefficient changes with raising frequency, at 10Hz reached 6.015, more details show in Figure 7, T means a flapping cycle.

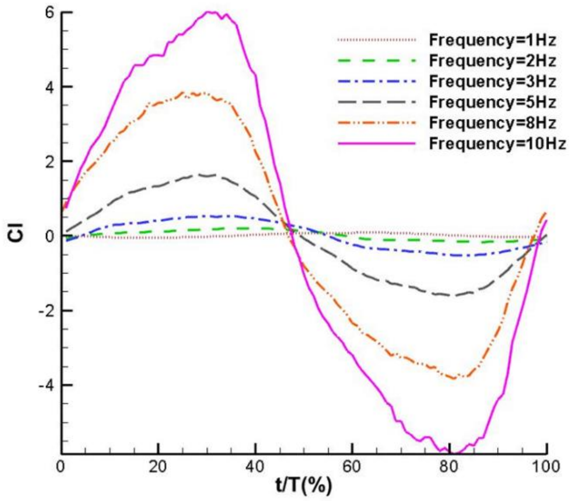


Figure 7 –Lift coefficient changes with frequency.

The result shows clearly that the lift coefficient grows as the flapping frequency ascending. Hence for better aerodynamics, the higher appropriate frequency is necessary.

Another major aerodynamic coefficient is the thrust coefficient. Same as the lift coefficient, with the increasing of flapping frequency, the peak of thrust coefficient raises as shown in Figure 8.

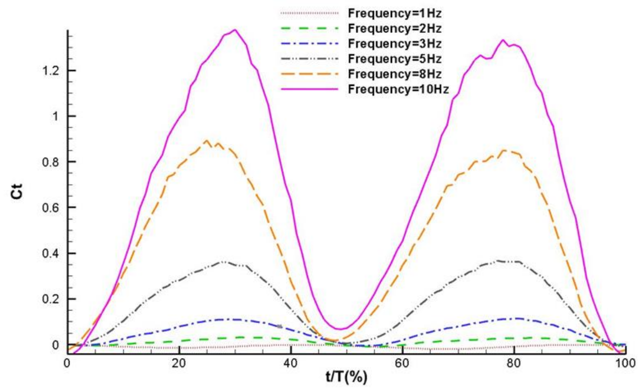


Figure 8 –Thrust coefficient changes with frequency.

The peaks of the lift coefficient and thrust coefficient are changing as shown in Figure 9.

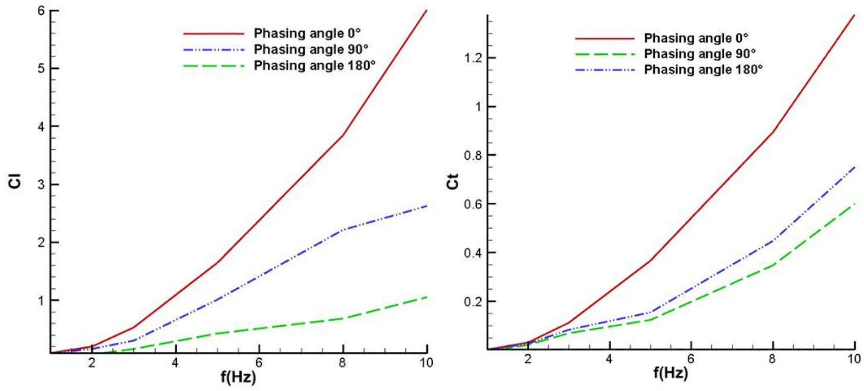


Figure 9 –Peaks change with frequency.

The results show clearly that higher flapping frequency gets a higher aerodynamic coefficient. For physical explanation, the rate of flapping matches the flapping power. When the power raised, the work which power applied raised. Hence dragonflies always maintain flapping frequency around 10Hz for better flight performance.

3.3 Lift and Thrust in Different Phase Angle

As mentioned before, dragonflies have a motion phase angle between the fore wing and hind wing. The effect will be discussed. This paper chooses high frequency according to the previous study and sets multiple phase angles in hindwing (0º, 90º, 180º).

The result of the lift coefficient can be divided into two parts: fore wing lift coefficient and hind wing lift coefficient as shown in Figure 10.

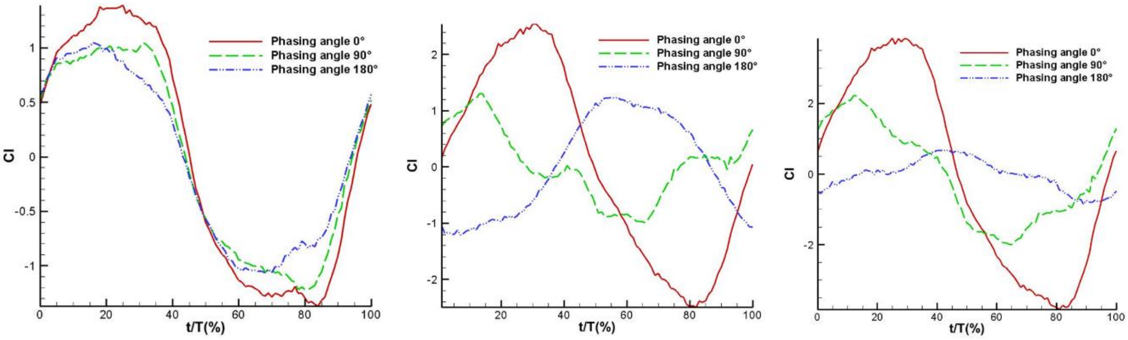


Figure 10 –Fore wing (left), hind wing (mid), and total lift coefficient (right).

The hind wing lift coefficient can be seen as an obvious mistiming due to the phase angle. However, although the flapping frequency is the same, the peaks in different phase angles are different. Not only hind wing shows later hind wing flapping lift drops but also fore wing has the same result too. Hence the different movements in the hind wing will influence the fore wing. More details are as follows.

Table 3 – Lift coefficient.

Phase angle/(°)	Fore wing (average)	Fore wing (peak)	Total (average)	Total (peak)
0	-0.013	1.392	0.032	3.848
90	-0.040	1.049	0.012	2.218
180	-0.026	1.047	-0.027	0.685

Same as the lift coefficient, the thrust coefficient also influenced by phase angle in both the fore wing and hind wing. Table 4 shows the thrust coefficient in the fore wing and the total wing section.

Table 3 – Thrust coefficient.

Phase angle/(°)	Fore wing (average)	Fore wing (peak)	Total (average)	Total (peak)
0	3.119	6.629	7.877	15.914
90	2.459	5.079	3.831	6.184
180	2.174	4.812	3.671	7.984

The result also shows the hind wing will influence the fore wing. A big phase angle will lead to a reduction of aerodynamic value.

3.4 Lift and Thrust in Takeoff Condition

In the beginning, this paper illustrates dragonflies will change their body position during the takeoff. In this part, we consider the aerodynamic coefficient in takeoff condition. After the calculation, the result of the lift coefficient is shown in Figure 11.

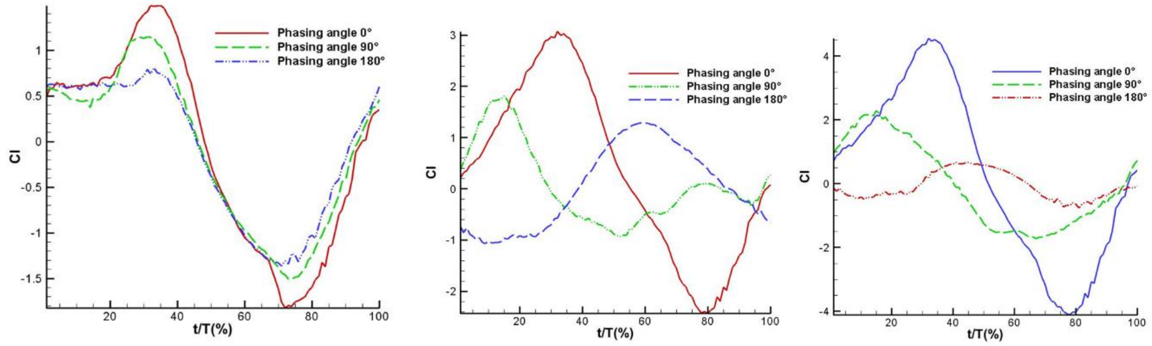


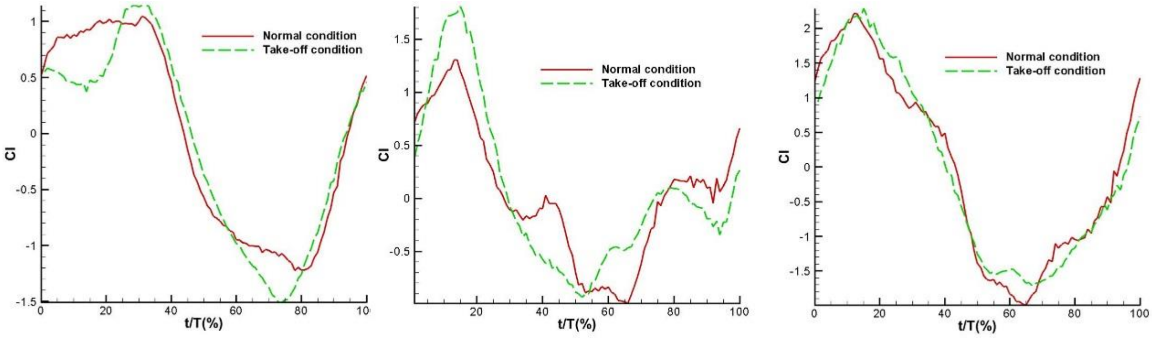
Figure 11 –Fore wing (left), hind wing (mid), and total (right) lift coefficient.

More details are as follows:

Table 4 – Lift and thrust coefficient.

Phase angle/(°)	Fore wing (average)	Fore wing (peak)	Total (average)		Total (peak)	
	Lift coefficient	Lift coefficient	Lift coefficient	Thrust coefficient	Lift coefficient	Thrust coefficient
0	-0.077	1.491	0.272	7.677	4.563	16.930
90	-0.101	1.144	-0.030	3.937	2.289	6.570
180	-0.100	0.809	-0.080	3.634	0.675	9.046

The comparison between the two conditions is shown in Figure 12.



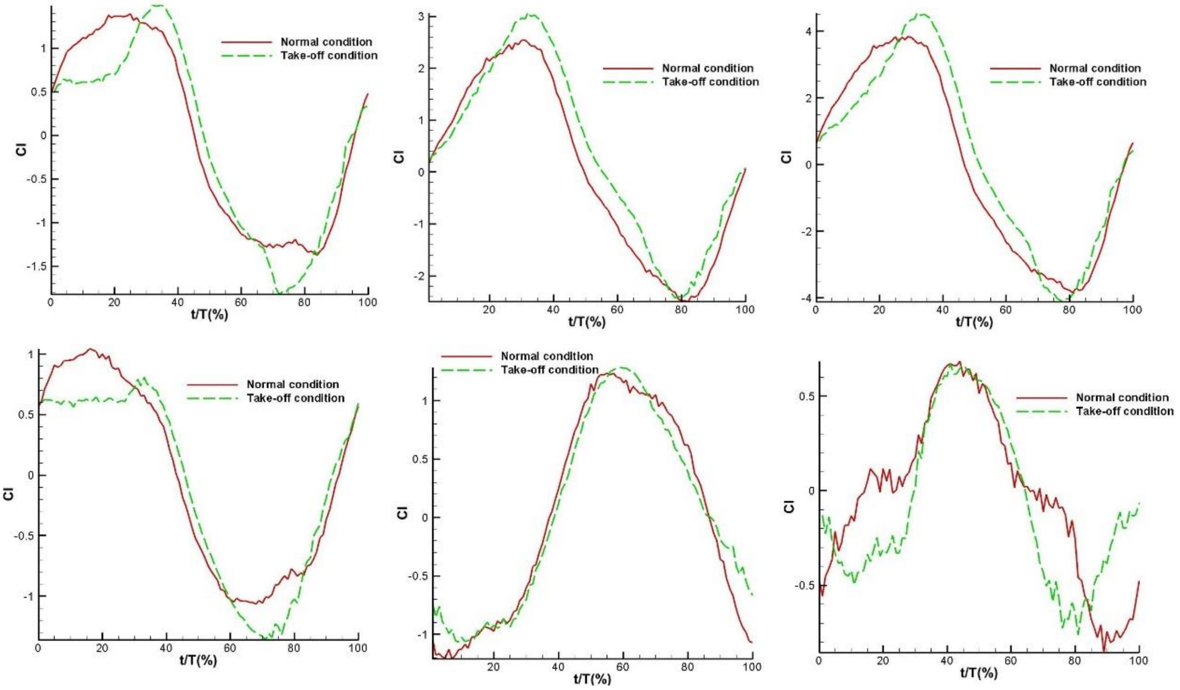


Figure 12 –Comparison about lift coefficient in 0° phase angle (top), 90° phase angle (mid), and 180° phase angle (bottom) with fore wing (left), hind wing (mid), and total (right).

Focus on the total aerodynamic coefficient changes, the average lift coefficient in the 0°phase angle raised 7.5 times than normal condition. The thrust also changed as shown in Figure 13.

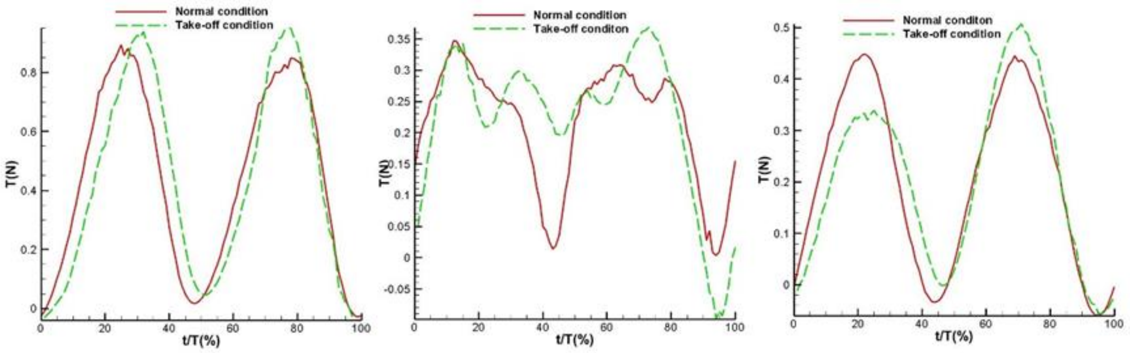


Figure 13 –Comparison of thrust in 0° phase angle (left), 90° phase angle (mid), and 180° phase angle (right).

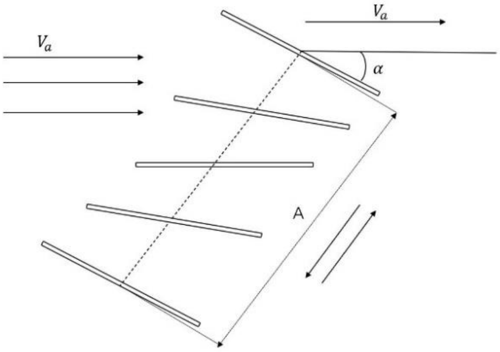


Figure 14 –Wing motion in takeoff condition

In the 90°phase angle, the thrust gap disappears in the takeoff condition, which leads the average of thrust raised. The result of this difference can be illustrated as an angle of attack applied in the flapping motion, shown in Figure 14.

4. Conclusion

The aerodynamic performance about dragonflies' airfoil from the tandem corrugated wing section is discussed in this paper. By focusing on the flapping frequency and different phase angles, it is found that frequency is vital for aerodynamic performance. The raising of frequency leads to a higher lift and thrust coefficient. This relationship is nearly linear. The reason for this phenomenon is the work done by flapping raised.

Another result that the phase angle in the hind wing will affect both the fore wing and hind wing. Although this effect is not obvious, the distance between the fore wing and hind wing will control this affection.

In the takeoff condition, the aerodynamic coefficient changed is relying on the angle of attack. Figure 14 clearly shows the angle of attack changes in takeoff conditions. Compare with normal non-angle of attack move, the performance improved.

The results are positive for MAVs design. However, the space between two different phase angles is a little wide. After calculation, the smaller gap is needed for further study. Hence it may have better aerodynamic performance between 0° and 90° phase angle which waits for further research.

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6. Copyright Statement

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