Research on Aerodynamic Characteristics of Bionic Flapping-wing Aircraft Based on Fluid-solid Coupling

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Abstract. Wings are an important part of the structure of flapping aircraft. Through the simulation of the flexible wing, its aerodynamic performance is studied. Applying the FSI technology and using the WORKBENCH software, the changes of lift and drag of the rigid wing and the flexible wing under the motion of two degrees of freedom, and the aerodynamic performance of the flexible wing under different frequencies are calculated. The research results show that: when the incoming flow velocity is 11m/s, the flapping angle is 45°, and the twist angle is 10°, the peak value of the lift coefficient of the flexible wing is significantly larger than that of the rigid wing, and it can generate greater thrust; At different frequencies, the maximum lift-to-drag ratio is generated at 10Hz. The results can provide reference for improving the flight performance of flapping-wing aircraft.

Keywords: Flapping-wing aircraft; Flexibility; Fluid-solid coupling; Simulation calculation.

1. Introduction

Nowadays, flapping-wing aircraft is the focus of research on micro air vehicles [1] , and it has been applied in many fields, such as military field [2] and civil field [3].In many years' research, rigid wings are generally taken as the research object, but there are obvious differences between real birds and insects, so the flexibility of wings can not be ignored. In order to further improve the aerodynamic performance of flapping-wing aircraft, it is necessary to further explore the flexibility of wings [4].

As the power system of flapping-wing aircraft, its flapping frequency is particularly important to the flight performance of the aircraft [5]. Some progress has been made in the research of flapping-wing aircraft at home and abroad. Based on the above research, this paper will further study the aerodynamic performance of bionic flexible flapping-wing aircraft in two degrees of freedom flight. Taking pigeons as bionic objects, the wing model is established, and the simulation calculation is carried out by WORKBENCH software. Through numerical simulation, the influence of flapping frequency on aerodynamic characteristics is further studied to improve the flight performance of bionic flapping-wing aircraft.

2. Flapping Model Construction

In this paper, the pigeon is taken as an example to build a three-dimensional model of the wing, which is modeled according to the real structural parameters of the pigeon. The front edge of the wing is supported by the humerus, and the lower surface of the wing is flat. The model parameters, wing modeling and motion coordinate system are shown in Table 1 and Figure 1, with the X axis along the chord direction, the Y axis perpendicular to the lower surface of the wing and the Z axis along the spanwise direction.

Table 1. Bionic Wing Model Parameters

parameter	numerical value
Humeral diameter	0.008m
Trailing edge thickness	0.002m
chord length	0.11m

Span leading edge length	0.13m
Span trailing edge length	0.33m
Maximum thickness	0.016m
Maximum thickness position	Chordal 10%

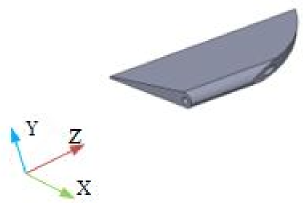

Fig. 1 Three-dimensional model of bionic wing

The movement of pigeon wings includes flapping, twisting and folding. This paper mainly studies flapping movement around X axis and twisting movement around Z axis. The flapping motion of the wing is similar to a simple harmonic motion, assuming that the flapping frequency of the wing is *f*, the flapping amplitude angle is *a*, wing movement time is *t*. The function equation of flapping is:

$$\theta_1 = a\sin(2\pi ft) \tag{1}$$

For the torsional motion of the wing, assume that the torsional amplitude angle of the wing is *b*, get the twist angle θ_2. The function expression of is:

$$\theta_2 = b\sin(2\pi ft) \tag{2}$$

3. Pre-calculation Processing

3.1 Fluid domain

According to the size of the wing, the fluid calculation domain is established, in which the external flow field is a cuboid with the size of 2m×2m×3m, and the wing is 0.5m away from the velocity inlet. The fluid domain grid adopts tetrahedral grid, and the grid is encrypted near the wing, resulting in a total of 740511 grids. The boundary conditions are set as shown in Figure 2. Considering the low flight speed in this paper, assuming that the air is an incompressible fluid and the gas parameters around the wing will not change, the turbulence model is Realisable, κ-ε, and the dynamic grid technology is used to re-divide the grid. The flow velocity in the fluid domain is 11 m/s, and the solution method is SIMPLEC.

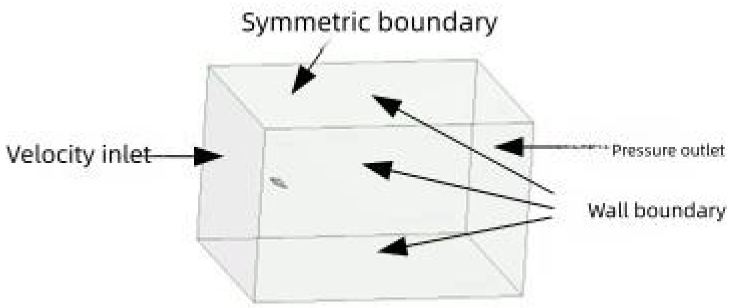

Fig. 2 Boundary condition setting

3.2 Domain

Because the model is irregular and may be obviously deformed, the solid adopts tetrahedral grid, and the number of grids is 102414. The grid division is shown in Figure 3. As an additional material of wing, the humerus is made of composite carbon fiber with high stiffness, with a density of 1800kg/m3 and a Young's modulus of 230Gpa. The wings are made of polyester film with a density of 1340kg/m 3 and a Young's modulus of 2.9Gpa. A kinematic pair is added to the wing to make the wing flapping and twisting, and all surfaces of the solid are set as fluid-solid coupling surfaces.

4. Numerical Calculation

4.1 Effects of Rigid and Flexible Wings on Aerodynamic Performance

The true flapping frequency of the pigeon is 8Hz, the flapping angle is 0 ~ 45, the twisting angle is 0 ~ 30, and the flying speed is 11m/s [6] .In this paper, the curves of lift coefficient and drag coefficient of flexible wing with flapping process are obtained by FLUENT module, and compared with those of rigid wing. When the flapping frequency is 8Hz, the period is 0.125s, the flapping angle is 45 and the torsion angle is 10, the curves of the lift coefficient and drag coefficient of the flexible wing and the rigid wing are shown in Figure 3.

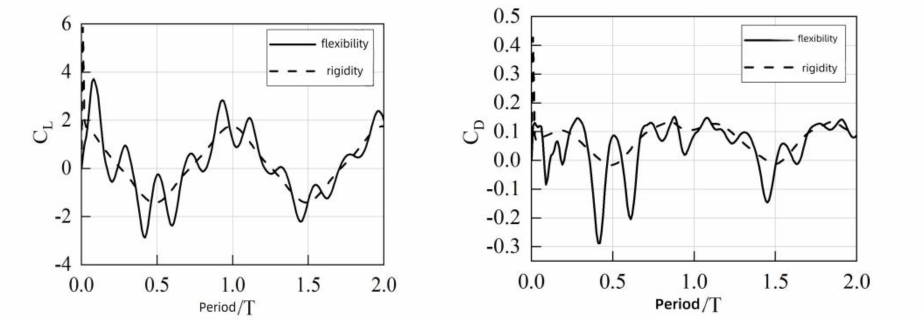

Fig. 3 Lift and drag coefficient curves of flexible and rigid wings

The wing begins to dive. Figures 3 show the curves of lift coefficient and drag coefficient of flexible and rigid wing in two periods. In the curve of lift coefficient in Figure 3, the change trend of rigid wing in one period is "high-low-high", and the lift coefficient changes smoothly, and the changes in two periods are the same; The overall change trend of the flexible wing in one period is also "high-low-high", but due to the influence of wing deformation on the nearby flow field, the lift coefficient fluctuates, and the fluctuation in the two periods is different, and the fluctuation in the second period is less than that in the first period. In the drag coefficient curve of fig. 3, the drag coefficient curve of rigid wing changes smoothly, resulting in small positive drag and almost no negative drag, that is, thrust; also, due to the deformation of the flexible wing, the curve fluctuates, and the two periods fluctuate differently. In the first period, the change trend is not obvious due to excessive fluctuation, and obvious thrust is generated in this period. In the second period, the same "high-low-high" change trend as the lift coefficient can be seen, and the thrust generated is reduced compared with the first period. The peak value of the lift coefficient of the flexible wing is obviously larger than that of the rigid wing, and it can generate a larger thrust, so it can be seen that the aerodynamic performance of the flexible wing is better.

4.2 Effect of flapping frequency on aerodynamic performance of flexible wing

In this paper, pigeons are taken as bionic objects, and the real frequency of pigeons is around 8Hz, generally not more than 10Hz. When the flapping angle is 45, the twisting angle is 10, the incoming flow velocity is 11m/s, and the flapping frequency is 4Hz, 6Hz, 8Hz and 10Hz, the curves of lift coefficient and drag coefficient are shown in Figures 4 and 5.

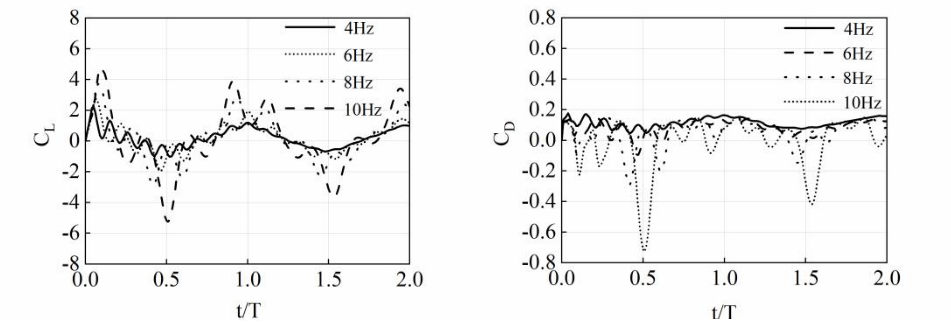

Fig. 4 Multi-frequency lift coefficient curve

Fig. 5 Multi-frequency drag coefficient curve

Fig. 4 is a multi-frequency lift coefficient curve. At different frequencies, the change trend of the lift coefficient curve is "high-low-high". Due to the influence of wing deformation on the flow field, the lift coefficient curve fluctuates. When the frequency is 4Hz, the curve fluctuation is the smallest, and it has become stable in the second period. As can be seen from the figure, the higher the frequency, the greater the peak value of the curve, that is, the maximum lift. Fig. 5 is a multi-frequency drag coefficient curve. When the frequency is 4Hz, the drag coefficient curve shows a trend of "high-low-high". With the increase of frequency, this trend becomes less and less obvious due to the enhancement of fluctuation. As can be seen from Figure 6 and Figure 7, with the increase of frequency, the fluctuation is gradually strengthened. This is because with the increase of frequency, the deformation of the wing is getting bigger and bigger in the flapping process, thus the influence on the flow field is getting more and more intense, so the fluctuation will be strengthened with the increase of frequency.

In order to better observe the influence of frequency on lift and drag, the average lift coefficient and average drag coefficient are used as measurement standards. The average lift coefficient and average drag coefficient and average lift-drag ratio are obtained by data processing. The average lift coefficient increases with the increase of frequency, and the average lift coefficient reaches the maximum at 10Hz, while the average drag coefficient decreases with the increase of frequency, reaching the maximum at 4Hz, and the flapping frequency increases from 4Hz to 10Hz, and the average lift-drag ratio increases by 7 times. Therefore, for flapping-wing aircraft of similar size, the lift and lift-drag ratio of wings can be obtained by increasing the flapping frequency appropriately to meet the flight needs of flapping-wing aircraft.

At the same time, the spanwise pressure nephograms at four frequencies, i.e., the downward flapping stage, the downward flapping to the lowest point, the upward flapping stage and the upward flapping to the highest point, are selected, as shown in Figure 6.

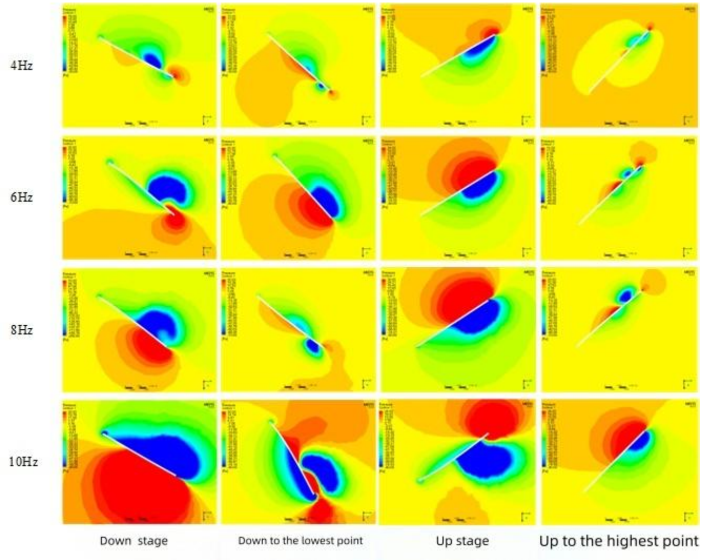

Fig. 6 Spanwise pressure nephogram of each frequency

As can be seen from Figure 6, when the frequencies are 4Hz, 6Hz and 8Hz, the pressure on the lower surface of the wing is greater than the pressure on the upper surface of the wing in the downward flapping stage, and positive lift is generated at this time; In the flapping stage, the pressure on the lower surface of the wing is less than that on the upper surface of the wing, and negative lift is generated at this time. When the frequency is 10Hz, the pressure nephogram distribution at the lowest point of flapping is different from that at other frequencies. This is because at this moment, the wing deformation is large, which leads to the severe impact on the surrounding flow field, so that the pressure on the upper surface of the wing is obviously greater than that on the lower surface of the wing, resulting in negative lift, which is the reason why the lift coefficient curve fluctuates greatly and is much smaller than that of the other three frequencies. Similarly, the upper surface pressure of the wing at other frequencies is obviously higher than the lower surface pressure in the flapping stage when the frequency is 10Hz, but it can be seen from the figure that the wing deformation is obvious, which leads to the change of the flow field, so the pressure difference between the upper and lower surfaces is small at this time. It can also be seen from the figure that in the cloud images of four frequencies and stages, the wing tip is under greater pressure, because the wing has certain flexibility, and when the wing tip is subjected to excessive pressure, it will lead to the bending deformation of the structure.

5. Summary

(1) Under the motion of two degrees of freedom, the curves of lift coefficient and drag coefficient of rigid wing are gentle, and the flexible wing fluctuates greatly. The peak value of lift coefficient of flexible wing is obviously larger than that of rigid wing, and it can generate larger thrust, so the aerodynamic performance of flexible wing is better.

(2) At each frequency, the lift coefficient and drag coefficient are fluctuating. As the frequency increases from 4Hz to 10Hz, the average lift coefficient increases, the average drag coefficient decreases, and the lift-drag ratio increases by 7 times. Therefore, the aerodynamic efficiency can be improved by increasing the frequency.

The modeling and simulation calculation method of flapping-wing aircraft proposed in this paper can evaluate the aerodynamic performance of flexible and rigid wings, as well as the influence of flapping frequency of flexible flapping-wing aircraft on aerodynamic performance, and provide some reference for flight performance optimization of flapping-wing aircraft.

References

[1] Zuo Deshen. Research on some key problems of bionic micro air vehicle [D]. Shanghai Jiaotong University, 2007.

[2] Yang Wenqing, Song Bifeng, Gao Guanglin. Calculation and analysis of flight performance of bionic flapping-wing micro air vehicle [J]. Journal of Northwestern Polytechnical University, 2018, 36(04):636-643.

[3] Zhang Yuan Kai. Study on Dynamic Optimization Design of Small Bionic Flapping-wing Flying Robot [D]. north china university of technology, 2018.

[4] RYU Y G,CHANG J W,CHYNG J. Aerodynamic characteristics of flexible wings with leading-edge veins in pitch motions [J].Aerospace Science and Technology,2019,86:558-571.

[5] WANG Q, GOOSEN J F L, KEULN F V. Optimal pitching axis location of flapping wings for efficient hovering flight[J]. Bioinspiration and Biomimetics, 2017,12(5):056001.

[6] Liu Xubo. Study on aerodynamic characteristics and structure of bionic flapping-wing aircraft [D]. Nanjing University of Science and Technology.