Analysis of aerodynamic characteristics of flapping process of imitation beetle folding wings

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Abstract. In this paper, the beetle rear wing is used as a bionic object to study the aerodynamic characteristics of the flapping wing aircraft during flapping. Firstly, a three-dimensional folding wing three-dimensional model was designed according to the folding mechanism of the beetle wing. Then the influence of different flapping angle of attack, torsion time and crease width on the aerodynamic characteristics of the rigid folding wing was analyzed by ANSYS FLUENT software. The results show that the flapping angle of attack has a great influence on the aerodynamic characteristics of the foldable wing. Appropriate reduction of the torsion time and crease width can improve the aerodynamic characteristics of the folded wing.

1. Introduction

Because the bionic flying robot has the characteristics of small size and flexible movement, and has great application prospects in military and civilian applications, it has attracted the attention of research institutions in various countries [1]. In recent years, due to the large folding rate and ingenious wing structure of the beetle, the researchers have attracted many researchers to focus on the study of bionic folding wings based on beetle hind wings. Zhu Jianyang [2] studied the effects of different flutter trajectories on the aerodynamic characteristics of flapping wings in the forward flight state through experimental and numerical simulation methods. Tailie Jin et al. [3] used the scanner to obtain the external contour and wing parameters of the beetle wing and established an aerodynamic finite element model. Tuyen Le Quang et al. [4, 5] performed a CFD numerical simulation of the beetle flapping wing, and studied the effects of local ripple and curvature changes on the flapping aerodynamics.

The current bionic design of the wings is mainly focused on the structure, which restricts the improvement of its motion performance [6]. Therefore, it is necessary to conduct an in-depth study on the flight motion mechanism. In this paper, the three-dimensional model of bionic foldable wing is firstly established, and then numerical simulation is carried out in ANSYS FLUENT software to analyze the influence of different flapping angle of attack, torsion time and crease width on the aerodynamic characteristics of rigid folding wing. The research results provide a reference for the design of bionic micro-robots.

2. Imitation beetle foldable numerical simulation

2.1. Model establishment
In this paper the folding mechanism designed is to regard the elastic hinge as a vein of wing. When the wings are folded, the elastic function of the elastic hinge is used to store energy; when the wings are deployed, the elastic mechanism releases energy and the entire hind wing gradually expands. Since the elastic hinge is attached to the wing, the elastic hinge can be regarded as a whole with the wing, and the folding movement of the wing only needs to consider the internal force of the wing. The core component of the design is a four-plate folding wing module. As shown in Figure 1, The four broken lines intersect at one point, and the angle between the two double-fold lines is $\gamma$, $\delta$, $\alpha$, $\beta$, and $\delta + \beta = \gamma + \alpha = \pi$. After theoretical research and simulation analysis, When the folding wing has $\gamma=63^\circ$, $\delta=94^\circ$, $\alpha=117^\circ$, $\beta=96^\circ$, the wing has the maximum folding rate. The four-plate folding wing model designed in this paper is shown in Figure 2. The half-length, chord length and thickness of the folding wings are 50mm, 20mm and 0.5mm respectively. The flexible hinge is 4mm long, 2mm wide and 0.2mm thick. The gap between the four plates is $d$.

2.2. Fluid domain settings
The flapping wing aircraft designed in this paper is a symmetrical mechanism, and the fluid domain is symmetrically processed, and only half of the fluid domain is calculated. The left side of the fluid domain is set as the velocity inlet and the right side is set as the pressure outlet. The upper, the front, and the lower surfaces are set as the static wall surface. The wings are the moving wall surfaces. An encryption zone is established near the folding wing to divide the unstructured grid, and the structural grid is divided in other areas. The total number of grids is about 660,000.

2.3. UDF function establishment
According to the study of the beetle flight flapping process, the geometric parameters and motion parameters of the beetle were obtained and the motion analysis model of the folded wing was established [7]. The movement posture of the beetle is shown in Figure 3. The base coordinate system $OXYZ$ is established on the body, and then the moving coordinate system $Oxyz$ is established on the folding wing. In the moving coordinate system, the $x$-axis and the $z$-axis are respectively defined as string direction and expanded direction of the folding wings.

The rotation speeds of the X-axis, Y-axis and Z-axis of the beta-winged wing around the fixed coordinate system are respectively
\[ \begin{align*}
O(x) &= \dot{\theta}(t) \\
O(y) &= \sin \theta \dot{\beta}(t) \\
O(z) &= \cos \theta \dot{\beta}(t)
\end{align*} \]  

(1)

where:

- \( \theta(t) \) - beat motion equation;
- \( \dot{\theta}(t) \) - beat angular velocity equation;
- \( \beta(t) \) - torsional equation of motion;
- \( \dot{\beta}(t) \) - torsional angular velocity equation.

According to the motion parameters of the folding wing and the equation of motion of the folding wing angular velocity, the motion program is written by the DEFINE_CG_MOTION macro provided in Fluent [8-9]. This macro is a description of the state of gravity of the body, which can be used to define the linear velocity and angular velocity of the center of gravity of the rigid body. After writing the angular velocity of the folding wing as the DEFINE_CG_MOTION macro function, it is compiled and loaded in Fluent to realize the flapping and twisting of the folding wing [10-12].

For the convenience of analysis, a dimensionless time is introduced to characterize the time point in the beat cycle. The expression is:

\[ t' = \frac{t}{T} \]  

(2)

where:  
- \( t \) - actual time of the motion;
- \( T \) - beat period.

3. Simulation results analysis

3.1. Impact of flapping angle of attack on aerodynamic performance

When the motion parameter is the flapping frequency \( f = 30 \text{Hz} \), the forward flying speed \( v = 1.5 \text{m/s} \), and the twisting angle \( \beta = 30^\circ \). This section analyzes the effects of different flapping angles of attack on the lift coefficient and drag coefficient. The lift coefficient curve of the rigid folding wing at different flapping angles of attack is shown in Figure 4. As can be seen from the figure, the pressure difference on the surface of the wing increases as the angle of attack increases, which causes the positive and negative peaks of the lift coefficient to increase. In the torsion phase, the change in angle of attack did not have much impact on it. When the folding wing is shot down, the main force surface is the lower airfoil, and the direction of the force is downward. The lift coefficient first becomes larger and then decreases. When the folding wing is photographed, the main force surface is the upper airfoil, and the direction of the force is downward. The lift coefficient is first reduced and then increased. The average lift coefficient curve of the rigid folding wing at different flapping angles of attack is shown in Figure 5. As can be seen from the figure, the average lift coefficient increases as the angle of attack increases. When the angle of attack is less than \( 10^\circ \), the average lift coefficient is negative, and the folding wing cannot produce lift. When the angle of attack is \( 15^\circ \), the average lift coefficient is positive, and the lift is generated at this time. At \( 25^\circ \), the average lift coefficient is at a maximum of 0.0195. Therefore, increasing the flapping angle of attack of the folding wing can effectively improve the aerodynamic performance of the flapping machine.

![Figure 4. Lift coefficient curve at different angles of attack.](image)

![Figure 5. Average lift coefficient curves at different angles of attack.](image)
The resistance coefficient curve of the rigid folding wing at different flapping angles of attack is shown in Figure 6. As can be seen from the figure, the increase of the flapping angle of attack has a greater influence on the positive peak value of the thrust coefficient. In the upper shooting phase, the negative peak increases as the flapping angle of attack increases, and the change is obvious. In the torsion phase, the drag coefficient first increases and then decreases. In the later stages of torsion, the drag coefficient reaches a positive peak. When the folding wing is turned from the top to the bottom, the drag coefficient first has a slight increase, then decreases rapidly. As the flapping angle of attack increases, the negative peak of the drag coefficient decreases. The average thrust coefficient curve of the rigid wing at different flapping angles of attack is shown in Figure 7. As can be seen from the figure, the average thrust coefficient increases first and then decreases with the increase of the flapping angle of attack. When the flapping angle of attack is 15°, the average maximum thrust coefficient is 0.02289. Therefore, selecting the flapping angle of attack of a suitable folding wing can effectively improve the propulsion capability of the aircraft.

3.2. Effect of Torsional Time on Aerodynamic Performance
When the motion parameter is the flapping period of the folded fin is T, the twisting angle is β=30°, and the time to complete the twisting in one flapping cycle is T'. This section analyzes the effects of different torsion times on the lift coefficient and drag coefficient. The lift coefficient curve of the rigid folding wing at different torsion times is shown in Figure 8. As can be seen from the figure, as the twisting time of the folding wing increases, the positive and negative peaks of the lift coefficient change little. In the torsion phase, the lift coefficient changes significantly, and the positive and negative peaks of the lift coefficient are maximum when the torsion time is T/8. The average lift coefficient curve of the rigid fins at different torsion times is shown in Figure 9. As can be seen from the figure, as the torsion time decreases, the lift coefficient first increases and then decreases. When the torsion time is T/6, the average maximum lift coefficient is 0.0019.

The resistance coefficient curve of the rigid folding wing at different torsion times is shown in Figure 10. As can be seen from the figure, the change of the torsion time has a greater influence on the drag
coefficient. As the torsion time decreases, the positive and negative peaks of the drag coefficient increase as the folding wing is twisted. Folding wing drag coefficient positive and negative peak values decreases as time increases when the torsional twist, which indicates that the torsion time has a greater influence on the drag coefficient. The average thrust coefficient curve of the rigid folding wing at different torsion times is shown in Figure 11. As can be seen from the figure, as the torsion time increases, the thrust coefficient decreases, and at T/8, the average maximum thrust coefficient is 0.02289.

3.3. Effect of crease width on aerodynamic performance

The folding wing is composed of a four-plate mechanism, and the width of the crease between adjacent plates has an important influence on flight performance. This section analyzes the effect of crease width on the lift coefficient and drag coefficient. The stiffness curve of the rigid folding wing with different crease widths is shown in Figure 12. As can be seen from the figure, as the crease width increases, the positive peak value of the lift coefficient changes less and the negative peak increases. The average lift coefficient curve of the rigid folded wings at different crease widths is shown in Figure 13. As can be seen from the figure, as the crease width increases, the average lift coefficient increases and the change speed becomes slower. At d = 0.2 mm, the average maximum lift coefficient is 0.00189.

The resistance coefficient curve of the rigid folding wing at different crease widths is shown in Figure 14. As can be seen from the figure, as the width of the crease increases, the negative peak of the drag coefficient decreases, and the positive peak has a smaller change. The average thrust coefficient curve of the rigid wing under the width of the crease is shown in Figure 15. As can be seen from the figure, the average thrust coefficient has the same tendency as the average lift coefficient. As the width of the crease increases, the average thrust coefficient decrease. When d=0.2mm, the average maximum lift coefficient is 0.02315. In order to prevent interference and other factors during folding, the folding width is d=0.4mm.
4. Summary
In this paper, ANSYS Fluent is used to simulate the folding flapping process under different structural and motion parameters. The setting of the fluid domain and the establishment of the UDF function are described. The aerodynamic characteristics of the folded wing under various conditions are analyzed and compared. The numerical simulation results show that increasing the flapping angle of attack can increase the average lift coefficient, but the flapping angle of attack will cause the average thrust coefficient to decrease. Decreasing the torsion time can increase the average thrust and lift coefficient, but the average lift coefficient becomes smaller when the torsion time is less than one-sixth of a cycle. Reducing the crease width can effectively increase the average lift coefficient and the average thrust coefficient. The research on the aerodynamic characteristics of rigid folding wings provides reference for the design of bionic micro-robots.

The research in this paper is mainly based on the simplified single-wing wing model. In the actual movement, the wings and the fuselage of the aircraft will have an impact on the aerodynamic performance. Therefore, the next step should consider the practical factors comprehensively. The mutual coupling between the two flexible wings and the fuselage should be counted.

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