Lift and Drag Analysis of a Bionics Flapping Aircraft

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Abstract. This article focuses on the study of bionic wings. Based on the analysis of insect thoracic cavity structure and movement mechanism, two groups of insect flapping wings models were simulated, and unsteady aerodynamic problems were studied using computational fluid dynamics numerical simulation methods, with emphasis on computer simulation, iterative calculation equations and observation. The convergence is used to analyze the driving force curve, verify and analyze the influence of air fluid on the surface pressure and speed of the wing during the flight of the insect. Studying the influence of fluid mechanics during insect flight is of great significance to further optimize and improve existing aircraft structure forces.

1. Introduction
With the increasing demand for aircraft, a kind of aircraft called micro bionic flapping wing aircraft is gradually recognized by people. Different from the traditional aircraft, this kind of aircraft has the characteristics of small size, low cost, easy to carry and good mobility, and has been widely used in military and civil fields [1].

Since the concept of flapping wing aircraft was put forward in 1992, many research groups have been established at home and abroad, and some achievements have been made [2]. For example, California Institute of technology and aviation environment company developed "miniature bat" micro flapping wing aircraft. It is a Bionic Flapping Wing Aircraft driven by micro motor and micro mechanical mechanism [3]. The shape of wings imitates the shape of bat wing membrane and has controllable flight ability. It has a wingspan of 15 cm and a weight of 10.5 G. In August 2002, the plane set a flight record of 22 minutes and 45 seconds.

In the work, we analyze the flight mechanism of monoptera insects on the basis of previous studies. Moreover the aerodynamic shape of single winged insects is analyzed, and the flight mechanism of single winged insects is studied. After confirming that the wing is feasible in the fluid dynamics analysis software, the motion simulation analysis is carried out, which provides some theoretical and practical reference for the development of flapping wing aircraft.

2. Problem statement and research principles

2.1. Fluid mechanics theory
The movement of any fluid must follow the three conservation laws of nature: conservation of mass, conservation of momentum and laws of conservation of energy. Firstly, we introduce the one-to-one continuity equation of mass conservation law in flow. It means a certain time the quality of the interval
flowing into the control unit is equal to the quality of the time flowing out of the control unit, and its differential form. The expression can be written as

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]  

(1)

Formula \( p \)—fluid density, unit is kg/m³; \( u, v, w \)—the component of the fluid velocity in the \( x, y, z \) axis direction, the unit is m/s; \( t \)—time, unit is S.

For the incompressible flow of constant flow, the continuity equation can be written as:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

(2)

Then it introduces the embodiment of the law of conservation of momentum in the flow problem—-the Navier-Stokes equation (that is, the momentum equation). It means that the combined force of all external forces on a fluid unit is equal to the rate of change of the momentum of the fluid unit with time. The differential expression of the equation in \( x, y \) and \( z \) directions can be written as:

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \tau + F_x
\]  

(3)

\[
\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v \mathbf{u}) = -\nabla p + \nabla \cdot \tau + F_y
\]  

(4)

\[
\frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho w \mathbf{u}) = -\nabla p + \nabla \cdot \tau + F_z
\]  

(5)

In the formula, the pressure of \( P \)-fluid unit, the unit is Pascal; \( \tau_{xx}, \tau_{xy}, \tau_{xz} \)—The component of the viscous force on the surface of the fluid unit, the unit is Pascal; \( F_x, F_y, F_z \)—The volume force of the fluid unit in the \( x, y, z \) direction.

Finally, the law of conservation of energy embodies the energy equation in the flow problem. It means that the energy increase rate contained in the fluid micro-unit and the net heat flux into the fluid micro-unit plus the amount of work done by the mass force and surface force on the fluid micro-unit, it can be written as:

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot u (\rho E + \rho) = \nabla \cdot \left( K_{eff} \nabla T - \sum_j h_j J_{j} \right) + S_h
\]  

(6)

In the formula, the energy of the \( E \)-fluid micro-unit, including kinetic energy, \( E \)-energy and internal energy, the unit is J/kg; \( h \)—enthalpy, the unit is the same as \( E \) as J/kg; \( K_{eff} \)—effective thermal conductivity coefficient, unit is W/(mK); \( J \)—expanded flux of component \( f \); \( S_h \)—Volume heat source item, including chemical reaction heat.

Because the study of the aerodynamic performance of the wing is an incompressible flow problem and the heat exchange is negligible, the subsequent numerical simulation calculations only involve the first two conservation laws, but not the energy equation. For the numerical simulation of the flow problem, in addition to using the three fluid equations, initial conditions and boundary conditions must also be set. In the unsteady flow problem, the initial conditions are the parameters that must be given at the beginning of the calculation. Can be written as the following expression:

\[
\begin{align*}
\mathbf{u} &= u(x, y, z, t_0) \\
\rho &= \rho(x, y, z, t_0) \\
p &= p(x, y, z, t_0) \\
T &= T(x, y, z, t_0)
\end{align*}
\]  

(7)
2.2. Computational fluid dynamics

Computational fluid dynamics (CFD) explores and analyzes various fluid flows and heat transfer in nature, engineering practice and social life through computer numerical simulation and visualization processing. There are three stages in computational fluid dynamics, namely, pre-processing stage, solution stage and post-processing stage. The main work of preprocessing is the design of computing domain and the meshing of computing domain. The solution stage is mainly divided into four steps: determine the boundary conditions and initial conditions, set the solver parameters, solve the discrete equations, judge the convergence of the solution. Because the numerical simulation needs to discretize the calculation area, it is necessary to mesh before the numerical simulation. After completing the mesh, first check the mesh quality. Then the flow problem is set as steady or unsteady, implicit or explicit. Then the turbulence model or multiphase flow model is established. Then the characteristic parameters such as fluid density and viscosity are set. Then set the boundary conditions of the calculation area. Finally, the initialization and iterative calculation of the calculation area are completed. After completing the above two stages of work, the calculation results are obtained, and then the post-processing stage is carried out. It is mainly to process the calculation results to get cloud, streamline and vector images, which is helpful to intuitively and clearly perceive the calculation results.

![Figure.1 Logic diagram illustrates the logical structure of the article](image)

3. Theoretical Basis of Insect Flight

3.1. Geometrical structure of insect wings

The wings of insects extend from the back plates of various parts of the body to the sides. They usually have no musculoskeletal system, only the muscles at the bottom of the wings are connected to the body to control the flapping of the wings. The edge of the wing near the head is called the leading edge; the edge close to the insect body is called the trailing edge; the angle between the leading edge and the trailing edge is called the shoulder angle at the wing root; the outer edge of the included angle between the leading edge and the trailing edge is called the hip angle; the distance from the wing root to the tip represents the length of the wing; and the distance between the leading edge and the trailing edge is called the chord length. The average chord length is usually used to describe the wings of insects. The insect wings are mainly composed of vertical and horizontal veins (20-200 μm) and pterygium (2-5 μm). The wings of insects consist of pterygium, pterygium supporting pterygium and several transverse veins connecting longitudinal veins. The longitudinal wing veins play the main supporting role, and the membrane in the closed box surrounded by the longitudinal and transverse veins plays a reinforcing role. The wing film forms the "umbrella effect" and the unsupported rear part becomes solid after deployment.
The peak cross-sectional area of the wing vein is larger at the wing root and decreases gradually from the wing root to the wing tip.

3.2. Movement of insect wings

The flying mode of insects is a flapping wing with extremely high frequency and complex movement track.[5] Using this flapping-wing method, these flying creatures can perform forward, backward, hover and other difficult maneuvers in the air. The wings are supported by two spatially arranged muscles near the root. If they are regarded as rigid plates, the flapping of wings can be expressed by flapping angle \( \Phi \), deviation angle \( \theta \) and attack angle \( \alpha \). The flap angle is the angle at which the wing sweeps across the flap plane. The maximum amplitude of flutter angle is about 60 ° to 180 ° and the maximum flutter angle of most insects is about 120 °. The angle of attack refers to the angle between the chord length of the wing and the flapping surface, which is generally about 35 ° or more. The angle of departure is the angle between the axis of rotation of the angle of attack of the wing and the flapping surface. The deviation angle of most insects (except Drosophila) is less than 10 degrees. The characteristics of insect flapping wings can be summarized as follows. First of all, insects can use the muscles at the root of the wings to actively twist their wings in a certain range, so their attack angles will change constantly during the whole process of flapping wings. The action point of integrated aerodynamic force is usually behind the twist axis of insect wings. Secondly, the curvature of the wing can be changed from leading edge to trailing edge. The wind tunnel test shows that the lift force produced by the small bending plate is greater than that of the non bending plate with the same size. Third, insects can change the force area of wings. Some species of butterflies can change the total wing area by changing the overlap of the front and rear wings. Finally, insects use their tilted wings to generate asymmetric aerodynamic forces.

3.3. Governing equations

Since the Reynolds number (re10-4000) of insect wings is far less than the critical Reynolds number (re5105-3106), the flow problem of insect wings should be calculated as laminar flow. Since the velocity of air flow around insects is very low, Mach number is about 0.02, the compressibility of air can be ignored as incompressible, that is, assuming that the density of air flow is constant. In conclusion, the flow around insect wings studied in this paper belongs to two-dimensional unsteady incompressible flow and belongs to laminar flow.

The flapping wing is basically a cantilever structure. Flapping wing aircraft wing movement by the bottom of each wing is a parameter of. The three Euler angles of the wing relative to the fuselage define the relationship between the wing and the fuselage. From these equations, the Euler angle which provides the wing motion can be obtained, which produces the lift and thrust of the aircraft. The flapping wing motion equation causes a significant change in the moment of each component and the position of the center of gravity. Therefore, it is necessary to establish a system equation to describe the motion of flapping wing aircraft, so as to make it measurable and constant.

3.4. Aerodynamic parameters

When air flows over an airfoil, each point on the surface of it is subjected to pressure \( P \) (perpendicular to the wing surface) and frictional shear stress (tangent to the wing surface). The resultant force is the total aerodynamic force \( R \), the Component of the total aerodynamic force \( R \) in the direction perpendicular to the incoming flow velocity is lift \( l \) and the component parallel to the incoming flow direction is drag \( D \).

The lift and drag characteristics of airfoils are usually described by dimensionless lift and drag coefficients, which are defined as:

\[
C_l = \frac{2L}{\rho V^2 \pi S} , \quad C_d = \frac{2D}{\rho V^2 \pi S}
\]
3.5. Aerodynamic modeling and analysis of rigid wing for flapping-wing aircraft

3.5.1. Simplified geometric model:
According to the real geometric motion parameters of the hind wings of the AESCHNA JUNCEA dragonfly, a geometric model of the wings is constructed in this paper. The model is a rigid plate with a length of 4.6 cm, an average chord length of 1.12 cm and a thickness of 1\% of the average chord length, i.e. 0.0112 cm. The symmetric plane is 0.61 cm away from the wing root, and the angle of attack is 0.28 cm away from the leading edge C / 4. A simplified geometric model of the hind wing of a dragonfly is shown in the first picture of figure 2[4]. The second image is a model built directly from an insect wing image.

![Figure 2](image)

Figure 2 (a) Classic dragonfly wing model (b) Another set of insect wing models. They are simplified geometric model of insect hindwing [4]

3.5.2. Model gridding:
When the flapping wing motion is simulated by numerical method, the outer boundary of the flow field should be infinite in theory. Considering the resource limitation, the external boundary of the external flow field is set as a rectangle, and the wing model is enclosed in the static rectangular outflow field. In this paper, unstructured tetrahedral element is used to divide a layer of 0.04cm thick mesh. The mesh elements are distributed on the surface of the wing model and the external flow field, but they are mainly concentrated near the model surface, and gradually increase along the model edge to the outer flow field boundary. In this way, the development of vortices around the flapping wing model can be captured, the number of grids can be reduced and the calculation cost can be saved. After inspection, the overall quality of the power grid is good, and the total number of power grid units is about 193000. The results show that 193000 grids can meet the requirements of calculation accuracy. The mesh representation of the external flow field and wing model surface is shown in figure 3. The model (c) is composed of 182000 grids and has been proved to be effective in subsequent calculations.
3.5.3. Calculation results and analysis:
We have carried out a velocity analysis of both the wing and the external watersheds, which tend to converge to steady values. In the research of Insect flapping-wing flight, the aerodynamic effect is usually characterized by lift coefficient and drag coefficient. The lift represents the aerodynamic component perpendicular to the translational velocity and the drag represents the aerodynamic component opposite to the translational velocity. Therefore, the vertical force coefficient and thrust coefficient are often used to express the aerodynamic performance of insect flight. The results are iterated over and over. As shown in figure 4, the velocity of the wing tends to be stable, and the result of the velocity converges. As can be seen from the diagram, we have done a total of two sets of wing calculation analysis, the result of the resistance tends to converge to a stable value, and the lifting force tends to converge to a stable value. By comparing with the results of Professor Sun Mao, we can see that the vertical force coefficient increases obviously at the peak of the down stroke, and decreases slightly at the trough and peak of the up stroke, the development trend of vertical force coefficient and Thrust Coefficient in a movement cycle is consistent with Professor Sun Mao's result, but the amplitude is slightly different. The reason for the above differences may be that the shape of wing model is slightly different. The model adopted by Professor Sun Mao is truncated at the wing tip, while the model in this paper has a sharp wing tip.

4. Results and discussion
This paper discusses the flying principle of insects. Taking monopterous insects as an example, the shape and flight parameters of monopterous insects were searched and discussed.
- The flow field model of airfoil is established, and the motion equation and parameters of airfoil are defined. On this basis, the aerodynamic characteristics of the flow field are analyzed.
- The aerodynamic performance of commercial wing is analyzed by FLUENT software.
In order to verify the feasibility and correctness of the above CFD numerical simulation method, this paper takes Professor Sun Mao [6] as an example to carry out numerical simulation. Although the change trend of the total thrust coefficient given by Professor Mao is slightly different from that of the solar force iteration, they are in good agreement.

![Figure 4](image)

Figure 4 (a)(b) Lift and drag curve (c)(d) Wing surface pressure. They all about force of wing and flow field

5. Conclusion

FMAV has special aerodynamic mechanism, which makes flapping wing flight highly flexible and maneuverable. In this work, the point tracking modeling of unilateral insects is only carried out, and the comparison with the experimental data of Professor Sun Mao verifies the feasibility of the numerical simulation method. However, in fact, the shape of the wings of each insect is different, and the wings will twist to a certain extent in flight. Therefore, this part needs further study in the future. In addition, this paper is based on the assumption that the wing surface is smooth. But in fact, the wing surface of monoptera is a little uneven, so it needs to be improved in future research.

Acknowledgement

Yifan Wang and Siwen Xie are contributed equally to this work.

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