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Design and Research on Mechanism of Bionic Flapping-wing Air Vehicle

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Abstract

The fly mechanism and motion characteristics of the birds were analyzed. By the bionics principle, a new bionic flapping wing mechanism was proposed in order to imitate the motion of bird wing. The virtual prototype of this mechanism was established through ADAMS, then the kinematic simulation analysis was applied to the prototype in order to validate the feasibility of this mechanism. And a computational fluid dynamics software, named Fluent was employed to analyze the aerodynamic force of bionic wing. These results shorten the period of manufacturing of flapping wing mechanism, and can provide theoretical basis for the research and manufacture of bionic flapping wing robot.

Keywords: *flapping wing mechanism; Bionics; simulation; aerodynamic force*

1. Introduction

The Flapping-wing Air Vehicle (FAV) based on bionics is a sort of new aircraft which imitates birds. Compared with the traditional fixed wing and rotor aircraft, setting the lift, hovering and push functions in a flapping wing system is the main characteristics of Flapping-wing Air Vehicle and it has strong maneuverability [1]. Flapping-wing Air Vehicle has advantages of high maneuverability, low noise, low cost, multifunction and potential applications to the modern war. In view of the FAV has great advantages in military and civilian applications, research institutions and universities around the world design various types of FAV. Research on this field has also been conducted in China. At present, the successful flight of FAV mostly adopts single crank rocker mechanism, such as MAV developed by northwestern polytechnical university [2]. Although single crank rocker mechanism can achieve predetermined flapping frequency and angle, but itself is a symmetrical structure. The motion of both sides wings is asymmetry in the process of flapping flight and affects the flight stability and security.

This paper analyzes the movement characteristics of bird wings from the perspective of bionics. A symmetric double sections flapping wing mechanism is designed in order to imitate the motion of bird wing. The virtual prototype of this mechanism is established through ADAMS, then the kinematic simulation analysis is applied to the prototype in order to improve the quality of the flapping wing flight. For the problem of the unsteady aerodynamic of flapping wing flight, by using the method of numerical simulation, the aerodynamic force is analyzed. The wing and tail are designed in the end. All these works are supposed to find the best design scheme and achieve sustainable flapping wing flight.

2. Design and Simulation Analysis of The Flapping -wing Mechanism

2.1. Bionic Basis

The flapping-wing flight, which is often seen in birds and insects, relies on flexible deformation and movement of the wings to generate the lift and thrust. Therefore, efficient and reliable flapping-wing mechanism is the core part of the bionic FAV. When birds fly in

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the stationary phase (no considering the process of taking off and landing), there are four basic movement: plunging, torsion, swing, folding. The motion of wing can be divided into four stages in a flapping cycle [3]: a. the phase of downstroke; b. the phase of folding; c. the phase of upstroke; d. the phase of outspreading. In a flapping cycle, the phase of downstroke takes most of the time [4]. The wings outspread as far as possible so that wingspan and lift area reach the maximum value and generate most of the lift force in this phase. The phase of upstroke is passive recovery and takes less time. In this phase, the wings fold in order to shorten the wingspan and reduce resistance.

Although folding movement is not necessary, it can make fly more efficient .In the process of upstroke, resistance will increase sharply. If bird can fold its wings at this time, it can reduce the effective windward area, thus considerably reduce resistance.

For large birds, wings torsion angle and swing angle are small. Instead, the folding process is obvious. Due to the existence of the folding movement, the lift coefficient produced in downstroke and upstroke is different. So the folding movement makes considerable contribution to the generation of birds lift for large birds. For bionic FAV, it is more important to realize folding movement than to realize torsion movement.

2.2. The Design of Bionic Flapping-wing Mechanism

According to the above analysis, a good flapping-wing mechanism should meet the following requirements: the rocker driving mechanism of flapping-wing should have fast-returning characteristic [5]; bionic wings outspread as far as possible in downstroke and fold in upstroke in order to obtain better flapping flight lift; in order to guarantee the flight stability of the FAV, the ideal flapping-wing mechanism should be symmetrical so that the flapping symmetry and stability can be improved; in addition, the flapping-wing mechanism should be high efficient and reliable. Under the condition that flapping-wing mechanism meets the flapping requirements, as much as possible, it should reduce the number of connecting rod and reduce weight.

Based on the bionics observation, typical bird wing is divided into three parts and complete the outspreading phase of flapping-wing flight as a human arm in order to get good lift characteristic. Besides, through the observation of insects flight found that insects flapping flight is driven by alternating contractions of the internal and external muscle. This paper uses symmetric double sections flapping-wing mechanism to imitate the outspreading phase of bird wing. The two sections are linked by joins that are similar to bird skeletons. In order to control the plunging of the second section bionic wing, we change the first section of connecting rod mechanism into parallel mode of two connecting rods. We can imitate the alternating contractions of the insect internal and external muscle in this way. So the motion of the second section bionic wing can be control by the first section bionic wing. The flapping-wing mechanism diagram is shown in Figure 1.

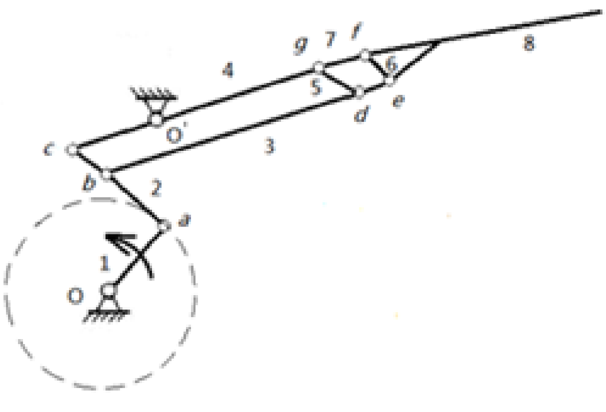


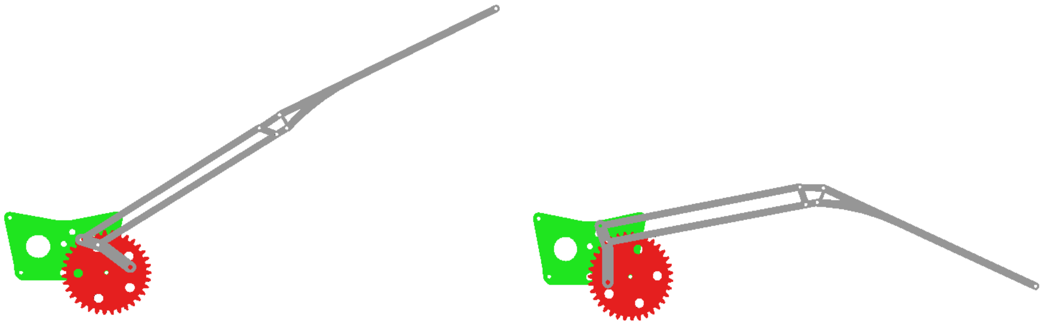
Figure 1. The Flapping-wing Mechanism Diagram

The first section rod structures and bird skeletons-like rod structures, which are composed of two quadrilateral structures (c-b-d-g, d-e-f-g), use four side instability to ensure mechanism smooth running. The bar (o-a) named number 1 is a actuator. Number 2 bar (a-b-c) is driven by number 1 and drive number 3 bar(b-d-e), number 4 bar(c-o'-g) doing parallel movement. Number 5 and 6 bar hinge on each endpoints and drive number 8 bar doing cycle motion in the process of the movement.

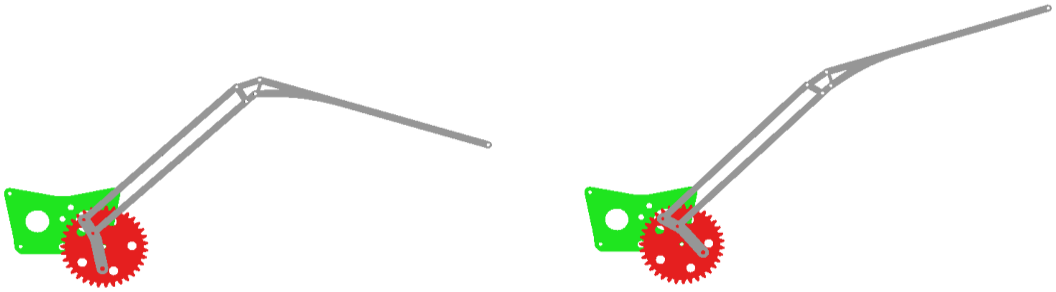
2.3. The Simulation Analysis of Bionic Flapping-wing Mechanism

Modeling is the fundamental of virtual prototyping system. In order to build virtual prototype model, three-dimensional flapping-wing mechanism model established in UG is imported into ADAMS, setting the corresponding simulation environment, including units, coordinate system, the acceleration of gravity, material properties and so on. Then, constraints on the virtual prototype, including fixed joints and revolute pairs, are imposed. Finally, the actuator is added on the virtual prototype. A virtual prototype model is built after system constrains, load and drive are added in ADAMS.

The actuator of virtual prototype is set to rotate at speed of $360^{\circ}/s$, then the force and others physical quantity, such as velocity, displacement and acceleration, of the revolute pairs are measured, as well, the key physical quantity. The performance of the flapping-wing mechanism is analyzed to examine whether the mechanism meet the design requirements. Kinematics simulation results show that the bionic flapping-wing mechanism can imitate birds flight well in a flight cycle as shown in Figure 2. According to the measurement of key points physical quantity, we can see that flapping-wing actuator mechanism has the fast-returning characteristic and can meet the flapping flight requirements.



downstroke phase **folding phase**



upstroke phase **outspreading phase**

Figure 2. Kinematics Simulation

After kinematics simulation analysis, the final three-dimensional flapping-wing mechanism model is established in UG, as shown in Figure 3.

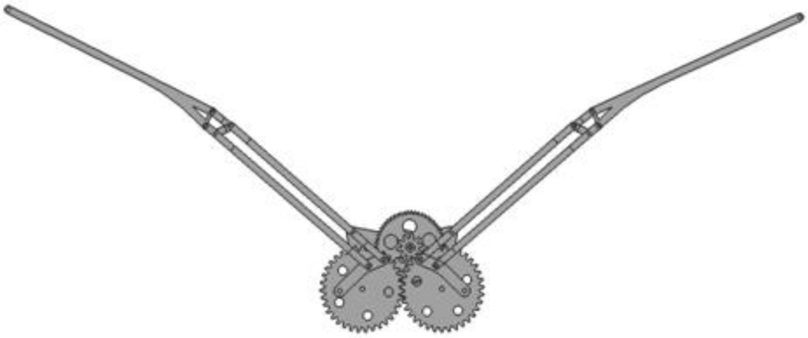


Figure 3. Three-dimensional Flapping-wing Mechanism Model

3. Aerodynamic Force Analysis of Bionic Wing

3.1. Grid Generation and Dynamic Grid Settings

Compared with the fixed wing and rotor aircraft, the study about unsteady aerodynamics associated with flapping flight is still in its infant stage. There are no mature theory and experience for the design of bionic FAV. Currently, studies about its aerodynamics are mainly based on experiments. However, experiments are always limited by model size, funds investment, the huge cost of manpower and material resources. With the quick development of computational fluid dynamics, numerical simulation has become one of important methods in the research of aerodynamics of flapping flight.

The dynamic grid technique is used to simulate and analyze the flow field of bionic wing by Fluent. The function of UDF is user-generated programs of Fluent software and it can dynamically link to Fluent solver in order to improve solver performance [6]. DEFINE_CG_MOTION macro is used to control the motion of wings dynamic area. Each time step of linear velocity and angular velocity are specified by this macro and node locations are updated through velocity update.

When using dynamic grid model in Fluent, the initial grid, the way of the boundary movement and the area of movement are need to define. The analytical expression of wing motion should be known before defining the movement of boundary. In order to get the analytical expression of wing motion, firstly the curve that angular velocity of wing varies with time is gotten through the above kinematics simulation by ADAMS. Then the date file that contains simulation time and corresponding angular velocity is outputted as the measured data in the process of curve fitting. Finally, the curve fitting of analytical expression of wing motion is accomplished by MATLAB curve fitting toolbox and output curve equation. The curve of angular velocity is shown in Figure 4.

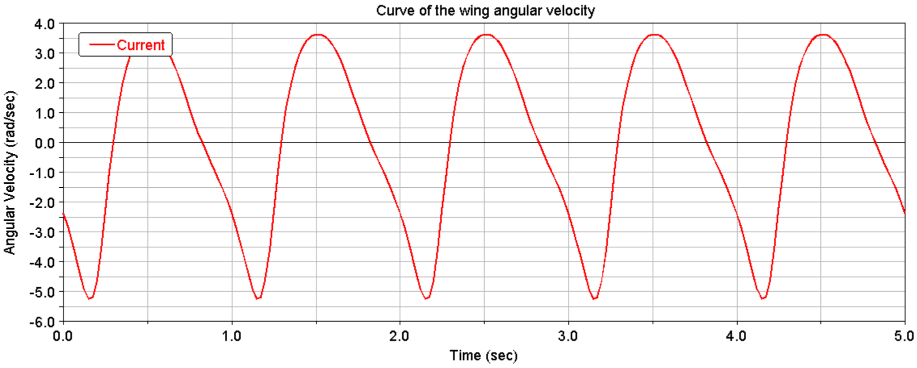


Figure 4. The Curve of Angular Velocity

The analytical expression of wing motion is shown below.

$$\begin{aligned}\omega = &-3.472\times\cos(2\pi\times t)-1.727\times\sin(2\pi\times t)+0.636\times\cos(4\pi\times t)-0.967\times\sin(4\pi\times t)+\\ &0.551\times\cos(6\pi\times t)+0.050\times\sin(6\pi\times t)+0.021\times\cos(8\pi\times t)+0.211\times\sin(8\pi\times t)-\\ &0.084\times\cos(10\pi\times t)+0.042\times\sin(10\pi\times t)-0.025\times\cos(12\pi\times t)-0.029\times\sin(12\pi\times t)\end{aligned} \tag{1}$$

The works need to be done are: modeling using preprocessing software GAMBIT, giving appropriate controlling zone, physics model and boundary conditions. In order to ensure the infinite boundary conditions, the calculation area is a square that its length of side is 10 times as long as wingspan. For the convenience of updating grid, unstructured triangular mesh is utilized here. Uniform incoming fluid flowing velocity is set for entry of computation region and pressure boundary condition is inducted for outlet. The wall condition is set for the wing model [7].

3.2. Numerical Simulation

The relevant parameters are set before the numerical simulation. The solver based on pressure and implicit solution is selected. Lift coefficient and drag coefficient can be directly monitored in the Fluent. The flapping frequency is $1Hz$ and inlet velocity is $1m/s$.Time step is 0.001s and we calculate 5000 step. The lift coefficient curve of bionic wing is shown in Figure 5.

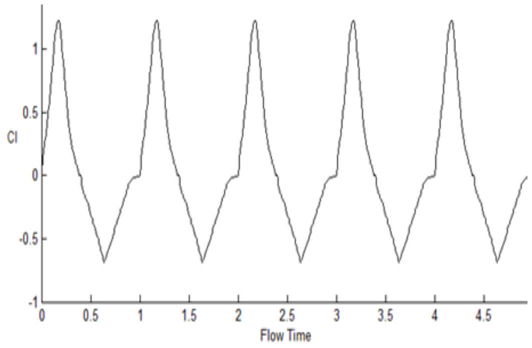


Figure 5. The Curve of Lift Coefficient

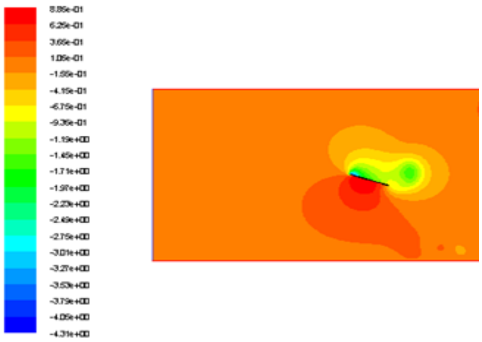


Figure 6. The Pressure Distribution of Flow Field

The pressure distribution of flow field in the phase of downstroke is shown in Figure 6. We can see that whirlpool appears on the wing surface. This shows that flapping flight aerodynamic is unsteady flow. The pressure on the upper surface is higher than that on the lower surface. So between the upper and lower surfaces, a pressure difference, they have a lift up.

4. Design of the Wing and Tail

The shape, layout form and materials of bionic wing and tail have great influence on the flapping-wing flight. There are flat wing and wing with airfoil in the study of the bionic wing. Flat wing is mainly used for the micro single section FAV. For the FAV with folding motion, its wingspan is larger and wing with airfoil is adopted in order to generate larger lift. Now symmetric airfoils, biconvex airfoil, flat convex airfoil, concave and convex airfoil and sigmoidal wing are commonly used. Five airfoils are shown in Figure 7.

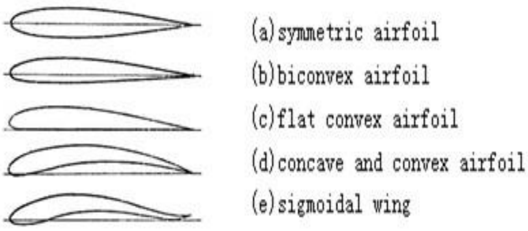


Figure 7. Airfoils

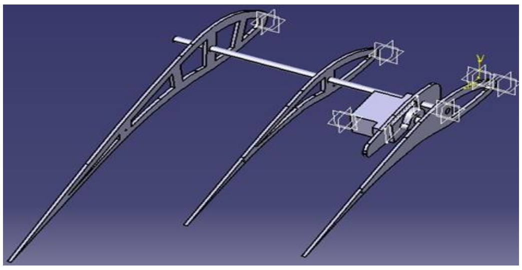


Figure 8. The Outside Rotor Wing Airfoil Model

The wing of a bird is analogy to the wing of an airplane. The convex upper surface of bird wing is smooth globoid and the lower surface is slightly concave. So the air speed on the upper surface is faster than the lower surface in flapping flight. Therefore, concave and convex airfoil better suits flapping flight. For the FAV with folding motion, in addition to produce thrust and part of lift, the outside wing also control the lateral stability. Through different rotation angle of the outside rotor wing, it can control the steering of the FAV. The outside rotor wing airfoil model is shown in Figure 8.

Tail has a great influence on the bionic Flapping-wing Air Vehicle. On the one hand, the tail can adjust the center of gravity. On the other hand, the tail has very important influence on the longitudinal maneuverability and stability of the bionic FAV. T-shaped tail, inverted V tail and cross-shaped tail are commonly used. The cross-shaped tail is mainly used for vertical flight [8]. According to the observation of most birds tails, inverted V tails are adopted. Compared with the conventional layout T-shaped tail, inverted V tail has better longitudinal stability and is beneficial to the horizontal flight.

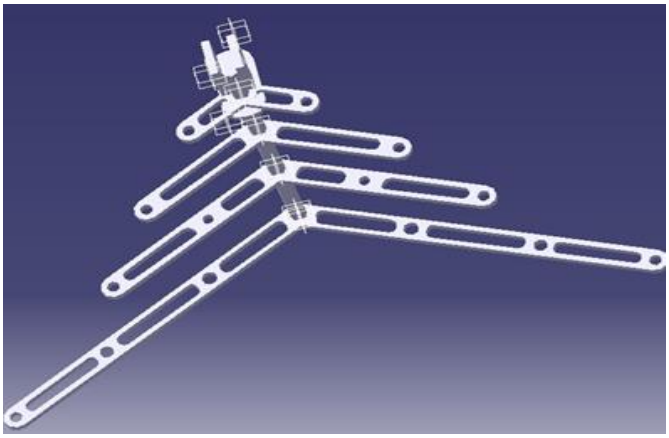


Figure 9. Inverted V Tail

5. Conclusions

From the point of bionics, the double section symmetric bionic flapping -wing mechanism is designed. Under the flapping flight requirement, the mechanism can better imitate the birds plunging and folding movement in flapping flight. The prototype of flapping-wing mechanism is established, while kinematics simulation is implemented using ADAMS software. With the virtual prototype technology, we can shorten researching cycle, reduce procreative cost, and improve the efficiency and quality of analysis.

Dynamic grids technology is applied to do the numerical simulation of unsteady flow around the bionic wing model with fluent analysis software and the lift coefficient curve is got. The simulation results show that using symmetric flapping-wing mechanism can get a larger lift and meet the requirements of the bionic flapping wing flight.

The wing and tail are designed at last. All the work can provide theoretical basis for the research and manufacture of bionic flapping wing air vehicle.

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