Dynamic Simulation Analysis of Flight Process of Bionic Aircraft

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Abstract. In this paper, the beetle (Coleoptera) is taken as a bionic object. According to the characteristic of the hind wing of the beetle that can be folded, combined with the four-plate mechanism theory, a bionic flapping aircraft with four-degree-of-freedom beetle foldable wing is designed. It can realize flapping, gliding, wing folding and abduction/adduction movement with self-locking function. At the same time, the physical model of the beetle-folding four-plate wing was established. The dynamic simulation of the flight process was carried out in ADAMS. The variation of the force and torque of the flexible hinge at different flapping frequencies is analyzed. The results show that the force and torque of the hinge have nonlinear characteristics during the take-off phase, but they tend to be stable eventually. The force and torque of each hinge first decrease and then increase as the flapping frequency increases, and the time of fluctuations becomes smaller. The simulation results provide a reference for the parameter design of the flexible hinge and the control of the aircraft motion.

1. Introduction

In nature, most insects and birds have excellent flight performance. Although many insects are small in size, they exhibit super flying skills and flexible maneuverability [1-2]. For this reason, from an evolutionary perspective, flapping is the most optimized flight mode, so the flapping-wing aircraft become the current research focuses. Therefore, many research institutions have carried out research: the beetle can collect the flexible membrane wing under the sheath wing, and its hind wings which have features such as larger folding rates have attracted many researchers. For example, Azhar Muhammad et al. [3] partitioned the physical structure of the hind wing of the beetle (Coleoptera), and analyzed the characteristics of folding and unfolding. Two types of artificial wings were designed by Azhar Muhammad [4]. Quoc Viet Nguyen et al. [5] analyzed the beetle fluttering process and designed a beetle-like flapping wing aircraft; at the same time, aerodynamic experiments and analysis were carried out. Tien Van Truong et al. [6] used two simultaneous high-speed cameras to digitize the points marked on the hind wings of the unicorns in Thailand, thus completing the three-dimensional reconstruction of hind wing motion. The data indicates that the beetle hind wing has more pronounced flexibility and deformation characteristics than other insects. Tuyen Quang Le et al. [7,8] performed the CFD (Computational Fluid Dynamics) numerical simulations of beetle flapping wings, and studied the effects of local corrugation and camber changes on flapping aerodynamic forces, and simulated the three-dimensional CFD numerical simulation of the trypoxylus Dichotomus coleoptera. In the process of synergy of the hind wing with the sheath wing, the interaction between the two can increase the vertical lift by 6%, thereby supporting the insect's own weight.
On this foundation, a four-plate foldable wing aircraft is designed in this paper. In order to improve the flight performance of the bionic aircraft, the dynamics simulation was carried out.

2. Foldable wing simulation model

2.1 The composition of the beetle’s hind wings
The beetle’s wing consist of a pair of elytra and a pair of hind wing. Elytra, also known as wing sheath. The elytra of the beetles are all hardened, highly keratinized, thick, hard and without veins. The main function of the elytra is to cover and protect the worm body and the hind wing. The hind wing of the beetle is the main source of flight dynamics, and its hind wings are membranous flexible structures. The shape of the hind wings in unfolding state is shown in Figure 1. The hind wings can be divided into Apical field, Middle field, Anal field and wing vein.

![Classification of the unfolded state of the Allomyrina dichotoma beetle](image)

2.2 Analysis of the hind wing mechanism model
According to the analysis of the physical shape and motion process of the hind wing, combined with the theory of mechanism, the schematic diagram of the four-plate folding wing theoretical model is shown in Figure 2. The four fold lines intersect at a break point O, wherein the four fold lines divide the wing into four parts. The names of the parts are shown in the figure 2. The fold line is equivalent to a hinge that allows the parts to rotate in the folding motion. The relative angle of adjacent plates during the folding process of the mechanism is defined as the "opening angle", which is expressed as $\theta$. The opening angle between the plates $\mathbf{1}$, $\mathbf{2}$, $\mathbf{3}$, $\mathbf{4}$ set as $\theta_1$, $\theta_2$, $\theta_3$ and $\theta_4$. The sum S of the angles of the plates around the point O is 360º. That is:

$$\alpha + \beta + \gamma + \delta = S \quad (1)$$

When $l_{FE} = l_{EG}$, the folding rate of the wing is the largest. At this time, it can be concluded that when the mechanism is completely folded, the difference between the $\beta$ and the $\alpha$, the difference between the $\gamma$ and the $\delta$ is necessarily equal, and it is obtained:

$$\beta - \alpha = \gamma - \delta \quad (2)$$

From the formula (1-1), (1-2), we can get:

$$\alpha + \gamma = S/2$$
$$\beta + \delta = S/2 \quad (3)$$

Therefore, it can be concluded that the sum of the angles that are not adjacent is 180º.

In addition, the simulation of folding motion shows that when $\delta > 90^\circ$ and $\gamma < 90^\circ$, each plate is not interfere with each other. In the case of ensuring that the degree of freedom is 1 and the wing can be completely folded, the angle of the plates around the O point should be avoided to be $90^\circ$. According to theory and simulation analysis, it was found that when $\gamma = 63^\circ$, $\delta = 94^\circ$, $\alpha = 117^\circ$, $\beta = 96^\circ$, the folding rate of the four-plate wings was the largest [9].
Figure 2: Four-plate folding wing theoretical model

The four creases of the hind wings intersect with one point, combined with the deployment mechanism of the main vein, and based on the four-plate folding theory, the schematic diagram of the flexible folding wing structure is shown in Figure 3.

Figure 3: Geometry of the wing

The geometry of the wing consists of four plates, of which the plate ④ is connected to the wing base. During the process of building the model, the model is simplified, and the flexible hinge between the mechanisms is omitted.

2.3 Foldable flapping wing aircraft structure design

In this paper, a bionic flapping aircraft with four-degree-of-freedom beetle foldable wing is designed. As shown in Figure 4, the aircraft consists of a four-plate folding wing module 1, a folding wing bracket module 2 and a wing abduction/adduction motion drive module 3, the folding wing drive module 4, the pitch drive module 5 and the tap drive module 6 are assembled. In addition, due to the modular design of the structure, the structure and motion function of the flapping wing micro-flying robot has more room for expansion.
Four-plate folding wing module 2. Folding wing bracket module 3. Abduction/receiving motion drive module 4. Folding wing drive module 5. Pitch drive module 6. Flapping wing drive module

Figure 4: Main view of the aircraft structure model

3. Parameter settings for dynamics simulation

The flight process dynamics of the bionic flapping wing aircraft was analyzed by the multi-body dynamics simulation software ADAMS. The material properties of the various components are defined in ADAMS. The material properties of the wing are defined as carbon fiber, and the material parameters are shown in Table 1.

| Material   | Elastic Modulus(Gpa) | Poisson's ratio | Density( Kg/m³ ) |
|------------|----------------------|----------------|-----------------|
| carbon fiber | 350                  | 0.307          | 2000            |

In order to simulate the flapping motion of the wing, the revolute pair between the plates of the wing is changed to a fixed pair, and the connection point between the plate ④ and the ground is set as a revolute pair, and the driving torque is added. After the wing is flexed, a set of key points are selected on the airfoil to add a force to simulate the force field acting on the wings.

The motion parameters that define the drive torque are:

\[
\text{step}(\text{mod}(\text{time},1),0.2,0.2499,2.1) + \text{step}(\text{mod}(\text{time},1),0.25,0,0.2501,-4.2) + \\
\text{step}(\text{mod}(\text{time},1),0.7501,0,0.7502,4.2) + \text{step}(\text{mod}(\text{time},1),0.9999,0,1,2.1)
\]

The motion parameters that define air resistance are:

\[
\text{step}(\text{mod}(\text{time},1),0,0.0476*1*1,0.2499,0.0476*1*1*\cos(30)) + \\
\text{step}(\text{mod}(\text{time},1),0.25,-0.0476*1*1*\cos(30),0.4999,-0.0476*1*1) + \\
\text{step}(\text{mod}(\text{time},1),0.5,-0.0476*1*1,0.7499,-0.0476*1*1*\cos(30))+ \\
\text{step}(\text{mod}(\text{time},1),0.75,0.0476*1*1*\cos(30),1,0.0476*1*1)
\]

The curves of driving torque and air resistance during flapping are shown in Figures 5 and 6. In the initial state, the wing is horizontal. When the wings move upwards, the air resistance of the wings is vertically downward along the wings. When the wings move downward, the direction of the air resistance is vertically upward along the wings. When the direction of air resistance is upward, it is defined as positive, and the flapping process of the wing is first downward and then upward, and the direction of the air resistance of the wings is: up→down→down→up.
4. Dynamic simulation analysis of flapping process

1) The wing is flapped at a uniform speed of 1HZ.

The curves of the force and the torque of each flexible hinge are shown in Figure 7 and 8. Wherein, the red solid line 4 is the force and torque curves of the hinge 4 between the plates ④ and ①; the blue dotted line 1 is the force and torque curves of the hinge 1 between the plates ① and ②; the green dotted line 2 is the force and torque curves of the hinge 2 between the plates ② and ③; the black dotted line 3 is the force and torque curves of the hinge 3 between the plates ③ and ④.

At the beginning of the flapping motion, the curve will fluctuate due to uneven force, and the fluctuation period is 5s; when the flapping motion enters the stable period, the flexible hinges are evenly stressed. After stabilization, the curve of the hinge force between the plates shows that the maximum forces of the flexible hinge 1, 2, 3 and 4 are 0.32N, 0.13N, 0.51N and 0.3 N, the maximum torque of the flexible hinge 1, 2, 3 and 4 are 0.0097Nm, 0.0015Nm, 0.01Nm and 0.0227Nm.

2) The wing is flapped at a uniform speed of 2HZ.

Figure 7: The curve of the force of each hinge when the flapping frequency is 1HZ

Figure 8: Curve of torque of each hinge when the flapping frequency is 1HZ
The curves of the force and the torque of each flexible hinge are shown in Figure 9 and 10. The flapping motion is basically stable, but within the flapping cycle, the force of the flexible hinge exhibits volatility, and the fluctuation time is 1.5s. After stabilization, the maximum forces of the flexible hinge 1, 2, 3 and 4 are 0.16N, 0.13N, 0.25N and 0.26 N, the maximum torque of the flexible hinge 1, 2, 3 and 4 are 0.0038Nm, 0.0012Nm, 0.0038Nm and 0.0125Nm.

![Figure 9: The curve of the force of each hinge when the flapping frequency is 2 HZ](image)

![Figure 10: Curve of torque of each hinge when the flapping frequency is 2 HZ](image)

3) The wing is flapped at a uniform speed of 4HZ.

During the take-off phase, the variations of force and torque showed irregular fluctuations, but the fluctuation time was shortened to 1.25 s. After stabilization, the maximum forces of the flexible hinge 1, 2, 3 and 4 are 0.2N, 0.1N, 0.3375N and 0.3 N, the maximum torque of the flexible hinge 1, 2, 3 and 4 are 0.0048Nm, 0.0016Nm, 0.0053Nm and 0.0155Nm.

![Figure 11: The curve of the force of each hinge when the flapping frequency is 4 HZ](image)
Through analysis of the above three cases, it is found that the force of flexible hinge 3 between the plate ③ and the plate ④ is the largest, the force of flexible hinge 2 between the plate ② and the plate ③ is the least. The torque of the flexible hinge 4 between the plate ④ and the plate ① is the largest, the torque of flexible hinge 2 between the plate ② and the plate ③ is the least, and as the frequency of the flapping fin increases, the force and torque of each flexible hinge show a tendency to decrease first and then increase. Then we can design the flexible hinge according to the simulation results and the actual situation, and choose the appropriate material and the number of flexible hinges to meet the flight performance.

5. Conclusion
For the bionic flapping aircraft with flexible hinge, the force and torque of the hinges of the aircraft at different flapping frequencies are simulated and analyzed by the ADAMS software. It is found that as the flapping speed of the wing increases, the force of the flexible hinge between the wings has a significant nonlinear trend. And the force and torque of the flexible hinges of each plate first decrease and then increase. With the increase of the wing flapping speed, the instability of the flapping motion during the take-off phase will increase, but it will eventually stabilize and the overall stabilization time will be shorter.

According to the simulation results, it is possible to select suitable materials and preparation methods when actually preparing the flexible hinge, so that the structural parameters of the flexible hinge can meet the flight requirements, and are stable and reliable.

Therefore, the research in this paper can promote the three-dimensional model of the structure of the aircraft and the further improvement of the mechanical properties, and provide a dynamic design method for the research and development of the foldable wing.

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