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Structural Design and Analysis of Small Flapping Wing Aircraft Based on the Crank Slider Mechanism

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Abstract: In this project, the miniaturization of the aircraft was realized under the premise of strong maneuverability, high concealability, and driving a certain load, and the flight mode and structural characteristics of birds were imitated. A small bionic flapping wing aircraft was built. The flapping of the wing was realized by the crank slider mechanism, and the sizes of each part were calculated according to the bionics formula. The wingspan was 360.37 mm, the body width was 22 mm, the body length was 300 mm, the wing area was 0.05 m^2, the flapping amplitude was 71°. ADAMS software was used to simulate the dynamics of the designed aircraft, and the variation of flapping amplitude and angular velocity during the movement of the aircraft was obtained, which verified the feasibility of the mechanism. The prototype aircraft was made for flight test, and the designed bionic flapping wing aircraft achieved the expected effect. It provides a theoretical basis and data support for the design and manufacture of small flapping wing aircraft.

Keywords: Flapping wing aircraft; Structural design; Dynamic simulation

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1. Introduction

Birds and insects with wings naturally have good flight performance [1-4]. The types of aircraft are fixed-wing, rotor, and flapping-wing. Compared to fixed-wing and rotorcraft flying, bionic flapping wing aircraft has unique advantages, such as being able to stay *in situ* or in small venues, excellent handling, good hovering flight performance, and low flight costs. The aircraft has lift, hovering, and push functions, and the flapping wing system [5]. Small flapping wing robot has a wide range of application prospects in military and civil fields due to their portability, operability, flexibility, good concealment, and low manufacturing costs [6-7]. It is because of its great applicability in various fields that many countries see it as the key research object [8]. Microbat, which is jointly developed by the California Institute of Technology and AeroVironment, is the earliest electric micro-flapping aircraft [9]. The fourth prototype reached a cruising time of 22 min and 45s. The Microbat has a wingspan of just 23 cm, weighs just 14g, and has flapping wings of around 20Hz, and it can carry a tiny camera. Mentor, produced by a collaboration between the University of Toronto and the Stanford Research Centre (SRI), has a maximum wingspan of 15 cm and weighs 50 g. It has four wings. The wings are powered by an Electrostrictive Polymer Artificial Muscle (EPAM) [9]. Festo, a German company, developed a Bionic Flying Fox [10], which has a total mass of 580 g, a wingspan of 228 cm, and a body length of 87 cm. Its wings are made of an extremely thin, strong film consisting of one layer of elastic fibers and two layers of sealing film. The Bionic Flying Fox can control wing deformation through skeleton movement during flight, to obtain strong flight ability. However, this aircraft is large, and it can be easily detected by ground personnel when flying in the air, and its application scope is limited.

Based on the previous research, a small flapping wing aircraft with a certain load capacity was designed and used for indoor and outdoor flight, and a flight test was carried out.

2. Overall structure design of aircraft

According to the statistical formula of bionics of flapping wing aircraft, there is an important relationship between the size of the bionic flapping wing aircraft and its mass. Using small birds as a reference, the total mass (*m*) was determined to be 50 g = 40 g (dead weight) + 10 g (load). Due to the difference between the designed aircraft and the actual birds, the dimensions of each part were obtained, as shown in **Table 1**.

Table 1. Parameter list of Ornithopter

Name	Parameter	Unit
Wingspan	36.37	cm
Wing area	0.019	m^2
Wing load	26.885	N/m^2
Aspect ratio	7.152	-

Traditional mechanical transmission mode can be divided into two categories: space-transmission type and plane-transmission type, considering the size and complexity of the mechanism, the plane transmission mode of single crank double rocker mechanism. In order to ensure the symmetry of flapping, the crank slider mechanism was adopted, and the slider (travel rod) was used to slide in the chute to drive the swing of the rocker, and then realize the flapping action of the wing.

To sum up, the overall design requirements of the aircraft are as follows:

(1) The overall size should not be too large, with a wingspan $B \leq 400$ mm

(2) The flapping frequency should be controllable, and the maximum frequency should be $15 \text{ Hz} \leq F \leq 30$ Hz

(3) The flutter amplitude should be $90° > \theta \geq 50°$

(4) Good maneuverability, able to complete pitch, yaw, and other actions

(5) The load capacity should be sufficient

3. Flapping mechanism design

According to the design requirements above and the selected transmission mode, the crank slider mechanism was taken as the core to transform the rotation of the motor into the flapping required by the flapping wing. The two-dimensional movement of the wing was achieved by aeroelastic deformation of the flexible wing SPAR and wing ribs [11]. The output torque was slowed down by the gear set to achieve the required power.

Figure 1 and **Figure 2** show the 3D model and principle diagram of the flapping mechanism. Among them, the gear and shaft adopt the interference fit, and the function of the travel part in the model is similar to that of the slider, which ensures the symmetry of flapping. O_1 is the hinge point between the crank and the output gear, O_2 is the hinge point between the wing connecting piece and the fuselage, O_1A is the crank, AB is the connecting rod, and BO_2 is the wing connecting piece. The crank rotates around O_1, and the connecting rod drives the travel piece up and down along the Y-axis. The travel piece drives the wing connector to swing in the XOY plane, thus fluttering the wing.

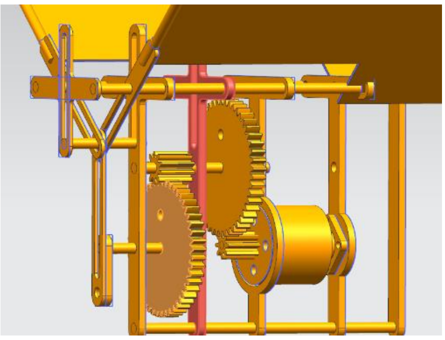


Figure 1. 3D model of the flapping mechanism

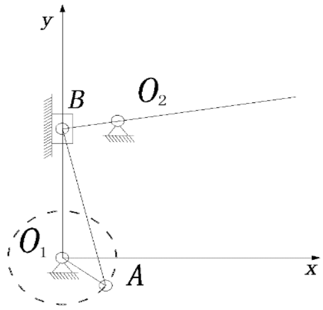


Figure 2. Schematic diagram of the flapping mechanism

The movement track of travel Part C is shown in **Figure 3**. C_1 and C_2 are the two limit positions of the travel part, D is the total travel, L is the width of the body, ø is the flapping amplitude, and $ø_1$ is the angle of the upper flapping limit position. Considering the design requirements of the overall size of the aircraft, as well as characteristics of small birds, L was set to 22mm, ø was set to 71°, and $ø_1$ was set to 42°. Therefore, when the travel part reaches the lower limit position, the end of the wing connector also reaches the limit position. Where ø is the flapping amplitude.

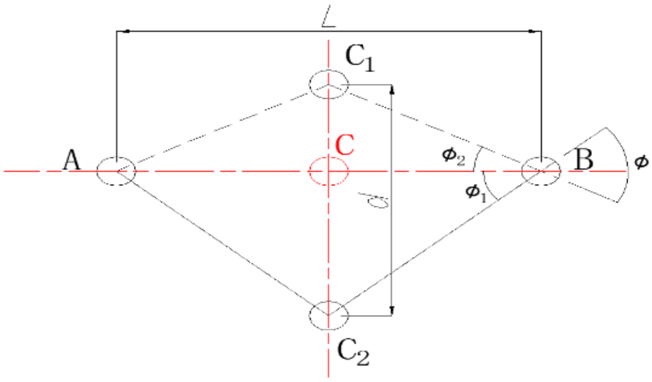


Figure 3. Movement tracks of travel parts

According to equation (1), $CC_2 = 9.9$ mm,

$$tan\O_1 = \frac{2}{L} \times CC_2 \quad (1)$$

According to equation (2), $CC_1 = 6.1$ mm,

$$tan\O_2 = \frac{2}{L} \times CC_1 \quad (2)$$

According to the values calculated from equations (1) and (2), it can be seen that the maximum stroke of the travel piece $D = CC_1 + CC_2 = 16$ mm.

According to equation (3), $C_2B = 14.8$ mm,

$$cos\O_2 = \frac{2}{L} \times CC_2 \quad (3)$$

Two limit positions of the transmission structure are shown in **Figure 4** and **Figure 5**. According to the geometric relationship of the connecting rod mechanism, the following equations were obtained:

$$d = L_1 - L_2 \tag{4}$$

$$d_2 = \frac{\mathrm{d}}{2} = 8mm \tag{5}$$

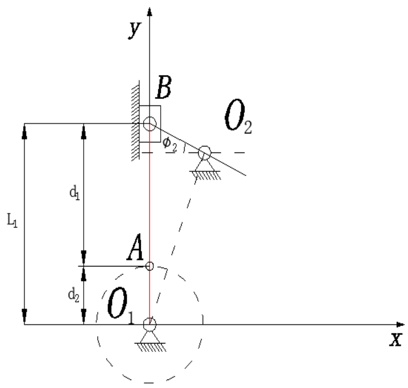


Figure 4. Limit position of travel parts

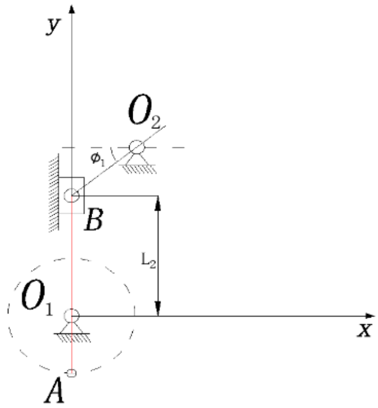


Figure 5. Limit position meter of travel parts

In summary, combined with the actual situation of the aircraft and its difference with real birds, the final parameters of the aircraft were determined to be as follows: The crank is O_1A = 8mm, the fuselage width is L = 22mm, the maximum flapping frequency is F = 20.1Hz, the wingspan is B = 37cm, the flapping amplitude is ø =71°, and the maximum stroke of the travel part is D = 16mm. D_1 is the length of the connecting rod, D_2 is the length of the crank, and L_2 is the distance from the limit position of the travel piece to the output shaft center.

4. Simulation analysis of aircraft motion

An aircraft simulation model was established (**Figure 6**), and the model was imported into Adams software. Firstly, the material of each component was determined. All components except the gear were made of carbon fiber material, and the gear material was POM. Then the constraints, force, drive, and torque were added at each position.

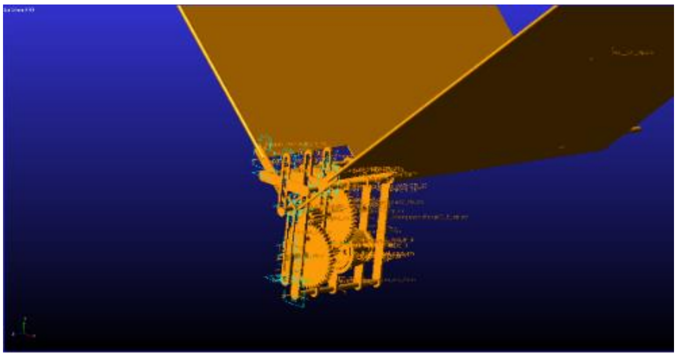


Figure 6. Simulation model of primary transmission structure

The flapping amplitude of the aircraft is shown in **Figure 7**, which is consistent with the designed value and conforms to the design requirements.

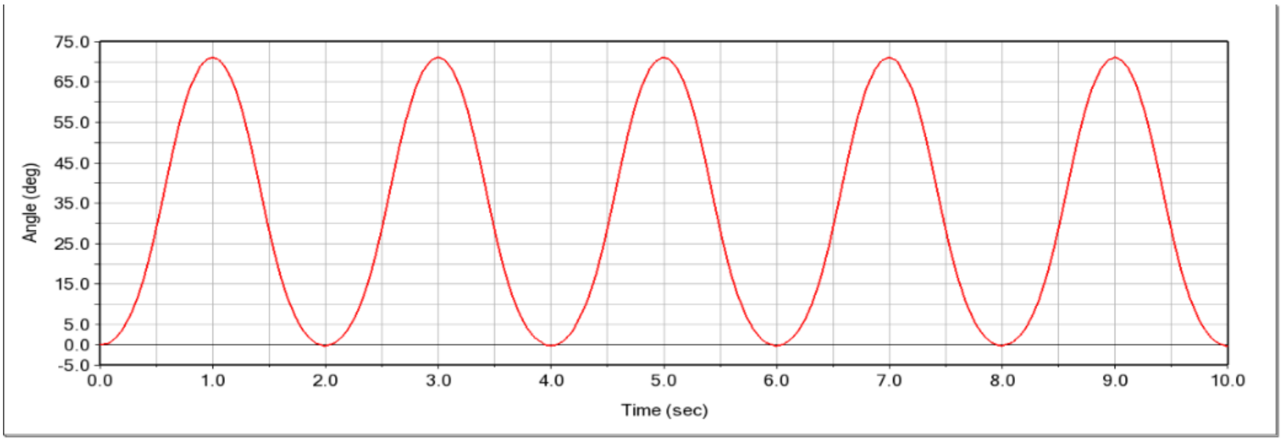


Figure 7. Flutter amplitude

The output axis of the aircraft, namely the main axis, is the main force axis. Therefore, the simulation results are shown in **Figure 8** and **Figure 9**.

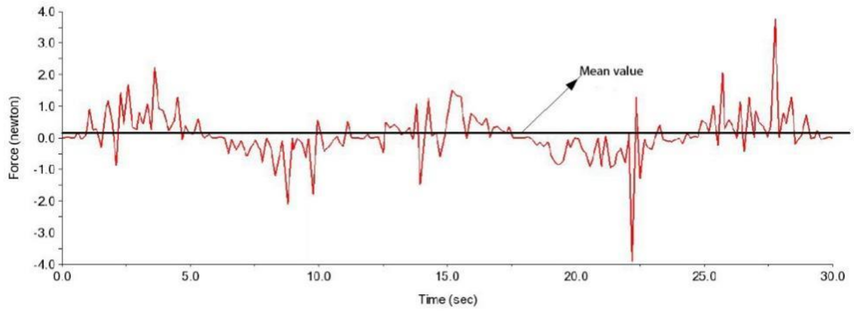


Figure 8. Force in x direction at the contact between the output shaft and fuselage

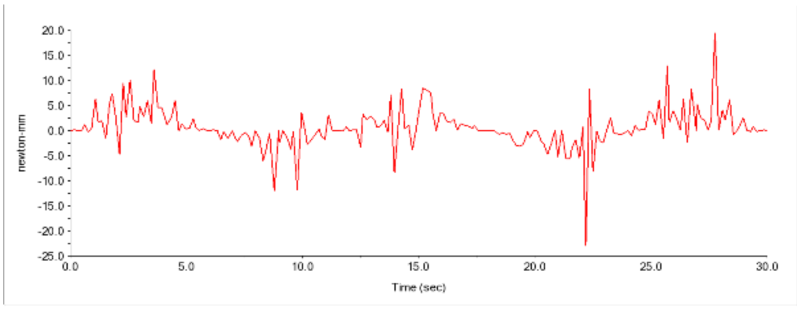


Figure 9. Torque in the y direction at the contact between the output shaft and the fuselage

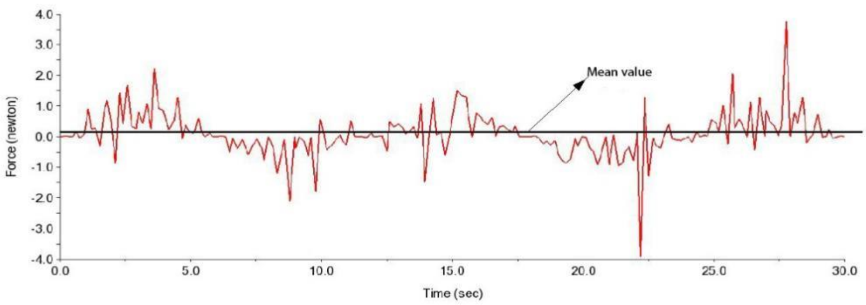
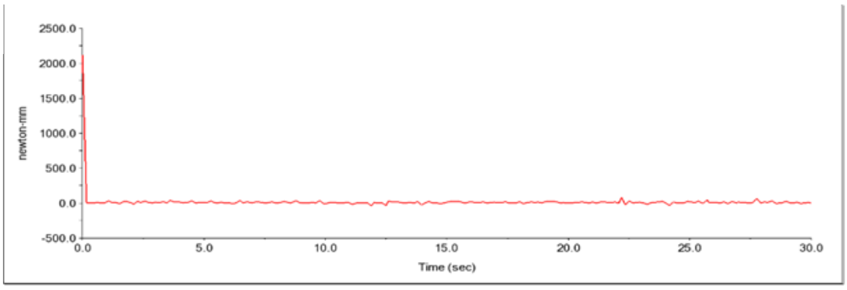


Figure. 10. Force in x direction at the contact between output shaft and fuselage

(a)



(b)

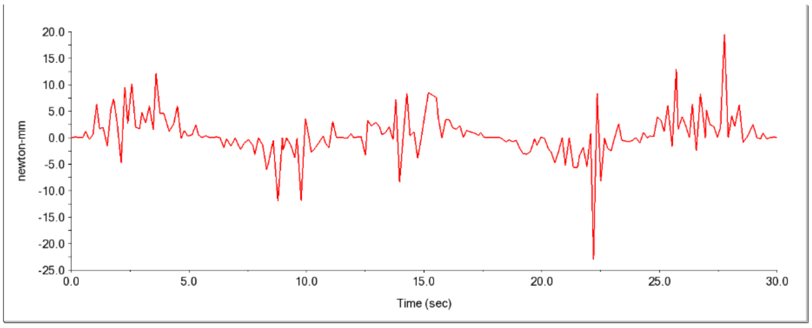


Figure 11. Balance moment at the connection between outlet shaft and fuselage. (a) Torque in the x direction at the contact between the output shaft and the fuselage. (b) Torque in the y direction at the contact between the output shaft and the fuselage

Based on **Figure 10** and **Figure 11**, the instantaneous maximum force in the X direction between the output shaft and the fuselage was about 4N, and the average value was about 0.2N. The instantaneous maximum torque in the X direction was about 2100Nmm at 0s, which is the initial position time. The maximum instantaneous torque in the Y direction occurs at 22.5s, and the wing was just at its initial position, that is, while preparing to dive. The torque value was -23nmm.

5. Conclusion

In this study, a bionic flapping wing vehicle was designed, and the dynamic analysis before and after model improvement was carried out by dynamic simulation software. The main force connection points were analyzed, the rationality and necessity of the improvement are verified, and the force and moment curves in the flapping process were obtained, which provided some theoretical basis for the production of the prototype. The size of this prototype is much smaller than the general flapping wing aircraft, and is light and easy to carry, and has a variety of complex site use.

Compared to previous studies, this design has achieved miniaturization in structure, which can not only fly in an outdoor environment, but also in a narrow indoor space, and the structure of this prototype has been simplified and optimized.

Disclosure statement

The authors declare no conflict of interest.

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