Design and analysis of single-degree-of-freedom flapping wing mechanism based on UG

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Abstract. According to the structural characteristics of bird wings, this paper presents a new type of flapping wing mechanism with single degree of freedom. The mathematical model of this structure has been established by this study. The left and right flapping angles of the mechanism are obtained through this simulation. The change rules of the left and right flapping angular velocities and the left and right flapping angular accelerations of the left and right rocker arm instantaneous flapping angular difference mechanism are also simulated by this model. This model lays a theoretical foundation for the dynamic characteristics of the mechanism. This study also makes a experimental plane. In this study, a high-speed camera was used to record the motion process of the experimental plane. The experimental results show that the test aircraft in this paper can realize the required movement of bionic wings. This study provides some theoretical and engineering guidance for the design of flapping wing mechanism.

1. Introduction
Flapping-wing MAV is the product of the application of new materials and the development of new technologies. This aircraft has become a hot topic in domestic and foreign research because of its broad application prospects in military and civil fields. The flapping wing drive system is essential to ensure the smooth flight of the flapping wing. The purpose of the research on the design of flapping wing transmission system is to design a transmission system with high efficiency, low consumption and light weight. The design of this article is to improve the flight performance of the flaps (working radius, payload, battery life, etc.) and expand its application fields. Therefore, it is very important to design efficient and reliable flapping wing drive mechanism [1].

In order to realize the successful flight of flapping wings, various types of flapping wing drive mechanisms have been designed and produced by research institutions and amateurs all over the world. Slider link mechanism is a variation of planar four-link mechanism. The design of the mechanism is based on the symmetry of the flapping wing, which effectively uses the allowable range of the deflection of the support rods on both sides of the mechanism to provide the freedom of the leading edge rod of the wing, and at the same time restricts the leading edge of the wing for planar movement to achieve the reciprocating flapping of the wing Design intent [2].

The gear transmission mechanism is a driving type widely used in flutter-wing aircraft. The motion of the gear transmission mechanism is symmetrical and the friction is small, which is conducive to the use of high speed and low weight motors and increases the output torque. The advantage of this design is to effectively overcome the motion asymmetry of the single crank double rocker mechanism. The disadvantage is that miniaturization is more difficult [3].
The mobile hinge mechanism consists of two flexible support rods. The deflection of this mechanism can provide freedom of movement in the X and Y directions of the hinge, which can realize the reciprocating flutter of the spar [4].

Worm gear worm deceleration space four-bar linkage is a symmetric transmission mechanism. This mechanism can use four spherical hinges to solve the interference and dead spots in the spatial position relationship of the four links. Worm gear mechanism has the characteristics of stable transmission and large transmission ratio. This mechanism can effectively reduce the weight of the transmission system. This advantage just balances the disadvantage of low worm gear transmission efficiency to a certain extent [5].

In order to make the flapping-wing aircraft more bionic, this study combines the skeleton characteristics of bird creatures to analyze the mathematical model of the four-bar linkage. This paper also compares the simulation with the expected trajectory, and provides a simple design method of flapping wing mechanism.

2. Composition of flapping wings

In order to adapt to flying in the air, birds have evolved different muscle and skeletal structures than ground animals, as shown in Figure 1. It can be seen from the figure that the developed chest muscles are the most important organs for birds to drive flapping wings to achieve flapping wings flight. This organ "burns" chemical energy to produce mechanical energy that drives the movement of the wings and transfers a lot of power to the wings. Studies have shown that the weight of the pectoral muscles of birds is generally about 20% of body weight. This ratio is far greater than the proportion of ground walking animals. The flapping wing drive system is equivalent to the organic combination of the bird's wing movement structure, flight muscles and nerve control system. The function of this mechanism is to realize the compound flapping motion of the wings. The secondary structure can generate the lift, thrust and flight control force required for flight. It can be seen that the drive system is the basis for flapping-wing flight. This mechanism is one of the core components of flapping wing, and it is also the key technology of flapping wing research.

The anatomy of bird wings is the standard for the design of drive mechanisms, as shown in Figure 2 [6]. As can be seen from Figure 2, the flapping wing mechanism is composed of a rocker arm, connecting rod, crank, frame, gear, and motor.

![Figure 1. Flight structure of birds.](image-url)
3. Mathematical model

![Flapping Wing Mechanism Schematic](image)

**Figure 3.** Schematic diagram of flapping wing mechanism.

According to the geometric relationship of various parameters of the driving mechanism (Figure 3), the left and right flapping angles of the flapping wing mechanism are $\beta, \gamma$. The maximum flapping amplitude angle of the mechanism is $\phi$, and the flutter angle is $\phi_d$, and the transmission angle’s are $\rho_1$ and $\rho_2$, and the mathematical model is as follow

$$\beta = 0.5 \cdot \pi - 2 \arctg \frac{A - \sqrt{A^2 + B^2 - C^2}}{B + C} + \theta$$  \hspace{1cm} (1)$$

The meanings of A, B and C in the above expression are as follows:

$$A = \sin(\alpha + \theta)$$

$$B = \cos(\alpha + \theta) - \frac{l_6}{l_4}$$

$$C = \frac{l_1^2 - l_2^2 + l_4^2 + l_6^2}{2l_4^2} - \frac{l_6}{l_4} \cos(\alpha + \theta)$$

$$\gamma = 0.5 \cdot \pi - 2 \arctg \frac{A + \sqrt{A^2 + B^2 - C^2}}{B - C} + \theta$$  \hspace{1cm} (2)$$

The meanings of A and B in the above expression are as follows:

$$A = 2 \times l_1 \times l_4 \times \sin(\alpha - \theta)$$

$$B = -2 \times l_4 \times (l_1 \times \cos(\alpha - \theta) - l_6)$$
\[ C = l_1^2 - l_2^2 + l_4^2 + l_6^2 - 2 \times \cos(\alpha - \theta) \times l_6 \times l_1 \]  

Maximum flutter amplitude angle \( \phi \):

\[ \phi = \arccos \frac{l_4^2 + l_6^2 - (l_1 + l_2)^2}{2l_1l_2} - \arccos \frac{l_4^2 + l_6^2 - (l_1 - l_2)^2}{2l_1l_2} \]  

Flutter angle \( \phi_d \):

\[ \phi_d = \arccos \frac{l_4^2 + l_6^2 - (l_1 + l_2)^2 + \frac{\pi}{2} - \theta}{2l_1l_2} \]

The size of the transmission angle in the drive mechanism is an important indicator to measure the quality of the mechanism. The size of the transmission angle in the movement of the mechanism is constantly changing. In order to ensure the good power transmission performance of the mechanism, the minimum transmission angle cannot be less than 40°. The formula for calculating the transmission angle of the mechanism is as follows:

transmission angle:

\[ \rho_1 = \arccos \frac{l_4^2 + l_6^2 - (l_1 - l_2)^2}{2l_4l_6} \]  

or \( \rho_2 = \pi - \arccos \frac{l_4^2 + l_6^2 - (l_1 - l_2)^2}{2l_4l_6} \)

4. **Simulation and analysis**

The movement of the mechanism is simulated and calculated by the movement analysis module in the ug software. The simulation result realizes the trajectory design of the driving mechanism. On the premise of adding a motion pair in ug to simulate the running mechanism, the experiment can obtain the real-time flapping angle, flapping angular velocity and flapping angular acceleration of the mechanism.

4.1. **Analysis of flutter angle**

Figures 4 and 5 show the variation rules of the instantaneous flutter angle and the difference between the instantaneous flutter angle of the mechanism. Through comparative analysis, it can be seen that the crank and rocker mechanism is an asymmetric flapping mechanism. There is a clear phase difference between the left and right rockers. When the crank rotates to \( n\pi \) \((n=1,3,5...)\), the phase difference between the left and right rockers of the mechanism is the largest, and its absolute value is 4,54°. When the crank rotates to \( n\pi \) \((n=0,1,2...)\), the phase difference between the left and right rockers is 0°, and the left and right wings are in the horizontal flapping position. In the design of the mechanism, the difference between the left and right flapping angles should be minimized to reduce the left-right asymmetry of the mechanism, so that the instantaneous lift of the left and right wings tends to be equal.
Figure 4. Comparison of left and right flutter angle of mechanism.

Figure 5. Instantaneous flapping angle difference between left and right rocker arms.

4.2. Analysis of flutter angular velocity and angular acceleration
Figures 6 and 7 show the changing rules of the left and right flapping angular velocity and angular acceleration of the mechanism, respectively. It can be seen that there is a clear phase difference between the flapping angular velocity and the angular acceleration between the left and right rockers. The maximum angular velocity difference between the left and right rockers is 1089 degrees/second, accounting for 61% of the maximum flutter angular velocity; the maximum angular acceleration difference is 65298 degrees/sec², accounting for 52% of the maximum flutter angular acceleration. The variation law of flutter angular velocity affects the flapping linear velocity of the wing, which in turn affects the lift force of the wing; and the change of flutter angular acceleration affects the magnitude of the inertial force generated by the mechanism, so it should be paid attention to in the mechanism design.

Figure 6. Comparison of left and right flapping angular velocity of mechanism.
Figure 7. Comparison of left and right flapping angular acceleration of mechanism.

5. Test flight of prototype
In this paper, a set of driving mechanism is developed based on the simulation results. The flapping wing prototype is shown in Figure 8. It can be seen from the results of the flapping wing test flight that the flapping wing flight is stable and has good maneuverability (Figure 9).

Figure 8. Flapping wing prototype. Figure 9. Flapping wings in flight.

6. Conclusions
The flapping wing mechanism is designed according to the composition of bird wings. The simulation results show that the designed flapping wing mechanism has reliable motion and high transmission efficiency. The test flight in the field shows that the sloshing of the left and right wings of the flapping wing is greatly reduced, which shows that the optimal design of the flapping wing mechanism can provide some theoretical and engineering guidance for the selection of the flapping wing mechanism parameters.

With the continuous improvement of the level of flapping wings and the need of practical use, it is imperative to increase autonomous flight equipment and video shooting equipment. The reduction in the asymmetry of the flapping-wing mechanism's motion can reduce interference to the autonomous flight control equipment and improve the stability of video shooting. This research provides a reference for the practicality of flapping wing aircraft.

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