

Article

Research on the Flight Performance of Biomimetic Moth Based on Flapping Function Control

Yaxin Liu ^{1,†} , Wenda Wang ^{1,†} , Ruiqing Han ¹, Qili Sun ^{2,*} and Ming Zhong ^{1,*} 

¹ State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin 150001, China; liuyaxin@hit.edu.cn (Y.L.); 24b908111@stu.hit.edu.cn (W.W.); 23b908099@stu.hit.edu.cn (R.H.)

² College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

* Correspondence: sunqili2023@nuaa.edu.cn (Q.S.); zhongming@hit.edu.cn (M.Z.)

† These authors contributed equally to this work.

Abstract: Flapping flight is an important mode of insect flight, and its unique flapping motion pattern enables it to fly efficiently in complex environments. This paper takes a biomimetic moth flapping-wing aircraft as the research object and proposes a periodic function composed of two sine functions with different frequencies as the flapping function. This paper explores the effect of this flapping function on the flight performance of flapping-wing aircraft and verifies whether it can be applied to the flight control of flapping-wing aircraft. Firstly, through the study of biomimetic mechanisms, the basic structure of the flapping-wing aircraft is roughly designed; then, the flapping motion is simplified, a rigid wing flapping motion model is established, and the key parameters affecting the average lift are determined. Next, a virtual wind tunnel simulation platform is built, and the key parameters of the flapping function that affect lift generation are simulated and calculated. Finally, an experimental prototype of a biomimetic moth flapping-wing aircraft is designed and manufactured. Through flight experiments, the effects of flapping amplitude, flapping frequency, and mid-position angle in the flapping function on the flight performance of the biomimetic flapping-wing aircraft are verified. The key control parameters are clarified, the control strategy of the flapping-wing aircraft is optimized, and the maneuverability and controllability of the aircraft are improved, providing a theoretical basis and practical support for the development of control methods for biomimetic flapping-wing aircraft.



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Keywords: biomimetic flapping-wing aircraft; flapping function; simulation calculation; flight experiment

1. Introduction

In recent years, microelectromechanical systems (MEMS) manufacturing and aerodynamics have led to the emergence and rapid development of micro aerial vehicles (MAVs), which play an increasingly important role in modern military and civilian fields [1–5]. Flapping-wing micro air vehicles have several advantages over fixed-wing and rotary-wing micro air vehicles, such as superior acoustic characteristics, better stealth capabilities, and the ability to recover potential energy during flight. These features make flapping-wing MAVs occupy an important position in the development and application of future science and technology.

According to the classification of biomimetic objects, existing flapping-wing aircraft research can be roughly divided into two categories: biomimetic bird flapping-wing aircraft and biomimetic insect flapping-wing aircraft [2]. The latter mainly focuses on three aspects:

1. Biomimetic design of insect wing structure and flapping motion, such as Festo's eMotionButterflies [6] and BionicOpter [7];
2. Miniaturization design based on special driving methods, such as the micro flapping-wing aircraft "Mentor" from the Stanford Research Institute (SRI) and the micro robotic fly from the Harvard Micro Robotics Laboratory [8];
3. Research on the collective flight behavior of insects and the control of flapping-wing aircraft clusters, such as Festo's BionicBee [9], autonomous formation flight control based on a leader-follower strategy [10] and three flapping wings with unequal spacing [11].

Biomimetic flight vehicles with Lepidoptera insects as biomimetic objects are a classic type of biomimetic insect flapping-wing aircraft, commonly known as biomimetic butterflies. They differ from other types of biomimetic insect flapping-wing aircraft due to their larger wingspan and lower flapping frequency. A representative example is Festo's eMotionButterflies. Its mechanical structure is quite simple, with the fore-wings and hind-wings on the same side slightly overlapping, simulating the amplexi form wing coupling device found in natural butterflies. This design creates an air gap during the flapping motion, thereby achieving favorable aerodynamic characteristics. Using a similar driving structure, Leng Ye [12] designed two flapping-wing aircraft. It has insufficient lift due to its lower flapping frequency. Huang Haifeng [13] made a flapping-wing aircraft named USTButterfly-S, which achieves turning by pulling ropes to change the area of the left and right fore-wings. Laura Tudose and others [14] developed a low-cost biomimetic butterfly, which uses sensors to collect flight data and explores better flapping frequency and amplitude ranges. Taro Fujikawa and others [15,16] paid more attention to the posture control mechanism during flapping. They designed a biomimetic flapping-wing aircraft with a new slider-crank mechanism, which uses elastic links to store and release energy to flapping the wings, thus realizing the lead-lag motion.

Overall, research on flapping-wing aircraft modeled after Lepidoptera insects, both domestically and internationally, primarily focuses on their structural design and the creation of biomimetic wings, with less attention given to the study of flight control.

Anatomical studies have shown that insects do not have wings with complex joints like birds, nor do they control their flight attitude through tails like birds. Therefore, their wing-flapping motion may be the key to their ability to fly effortlessly. To facilitate the description, define the periodic change function of the wing flapping angle as the flapping function. Reference [17] observed that the flapping function of butterflies is approximately a sine function through a high-speed camera, which inspired me. After extensively observing the flapping behavior of Lepidoptera insects, a new type of periodic flapping function was proposed. This flapping function is smoothly connected by two sine functions with different frequencies, which gives it a controllable quick return feature. This paper proposes to design a biomimetic moth flapping-wing aircraft to explore the effect of this flapping function on the flight performance of flapping-wing aircraft. Using the XFlow_2022 software for simulation and calculation, the effect of the flapping function on its aerodynamic performance is investigated, and finally, a flapping-wing aircraft prototype is manufactured, and flight experiments are conducted to verify the results of simulation and calculation.

2. Biomimetic Mechanism and Inspiration of Insect Flapping Flight

In order to make an experimental prototype of a biomimetic flapping-wing aircraft for flight experiments, it is necessary to first conduct biomimetic research on the structure of insect wings and the mechanism of flapping flight.

2.1. Structure of Insect Wings

The wings of insects are usually triangular in shape, with veins and other structures distributed on the surface [18]. According to their morphology, they can be divided into eight categories, such as membranous wings, as shown in Figure 1a. In biomimetic design, membranous wings are chosen as the design prototype and carbon fiber materials with high strength and fatigue resistance [19] are used as the veins, and lightweight and tough film materials are used as the wing membranes. The distribution form of the veins on the wing surface is called venation [20]. Reference [21] indicates that the most sensitive part of the mass response was mainly concentrated in a part of the wing veins. Removing some of its mass will not have a great influence on the structural and mechanical properties of the hindwing model. In the design of biomimetic flapping-wing aircraft, a reasonable venation is beneficial to increase the strength of the biomimetic wing and enable it to produce passive deformation conducive to flight.

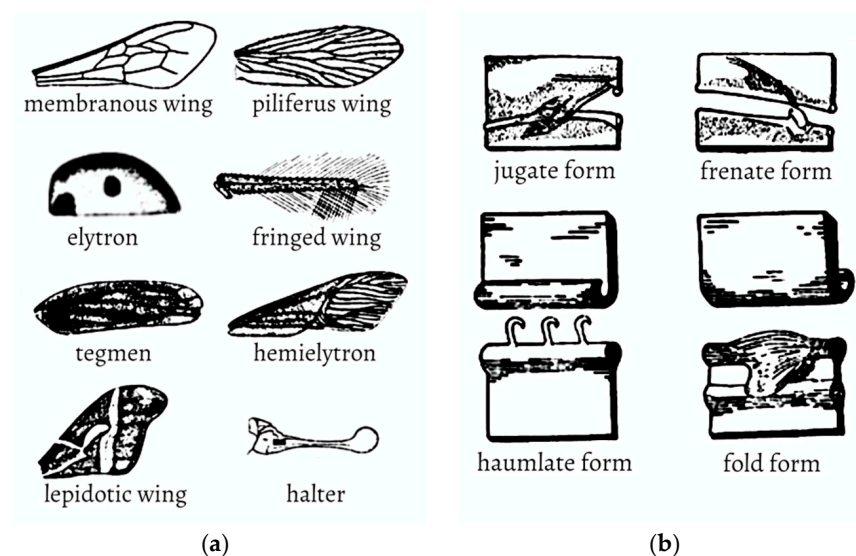


Figure 1. Wings of insects: (a) classification of wing; (b) wing coupling device.

Insect flight involves three modes of interaction between the fore-wings and hind-wings. For Lepidoptera insects, both pairs of wings participate in flight, but the fore-wings are dominant, while the hind wings are connected and follow along through a linking structure known as the “wing coupling device”. The main types of wing coupling devices include amplexi form, jugate form, frenate form, haumlate form, and fold form, as shown in Figure 1b. In biomimetic design, an improved version of the jugate form is selected as the structure for the wing coupling device.

2.2. Mechanism of Insect Flapping Flight

The mechanism of high-lift flapping flight of insects is widely accepted, including the Clap-Fling mechanism proposed by Weis-Fog [22], the leading-edge vortex and delayed stall proposed by Ellington and others [23], the rotational circulation theory and the wake capture theory proposed by Dickinson and other [24]. These theories collectively point out that vortices are the key to generating high lift, and the compound motion mode of insect wings is the key to generating vortices. During flapping, insects’ wings are driven by the leading edge to the trailing edge, so the flapping motion can be decomposed into a compound motion of translation and rotation.

Based on the above research results, the wing design of the biomimetic flapping-wing aircraft adopts a lightweight biomimetic flexible membrane wing structure: both the fore-wings and hind wings are triangular in basic shape; carbon fiber materials are

used as the vein materials, and lightweight film materials are used as the wing membrane materials; both the fore wings and hind wings participate in flight; the fore-wings are directly driven according to the flapping function, and the hind-wings are driven by the fore-wings through the jugate form wing coupling device; the wing is a flexible wing, with the leading edge driving the trailing edge to flap, which can achieve passive flexible deformation of the wing to achieve the compound motion of translation and rotation of the wings. In reference [25], this type of motion, characterized by active flapping and passive twisting, is referred to as the Flapping-Wing Rotor (FWR), which is believed to combine the characteristics of both flapping wings and rotors. At certain Reynolds numbers, it can generate a larger lift coefficient than both rotors and flapping wings, and it also has a higher power efficiency.

3. Calculation and Simulation

3.1. Lift Calculation of Rigid Wing Flapping Motion

Before making the experimental prototype, it is necessary to establish a lift calculation model to explore the key parameters in the flapping function and analyze their effect on lift generation.

The simplified airfoil model is shown in Figure 2a, and the simplified kinematic model of flapping motion is shown in Figure 2b.

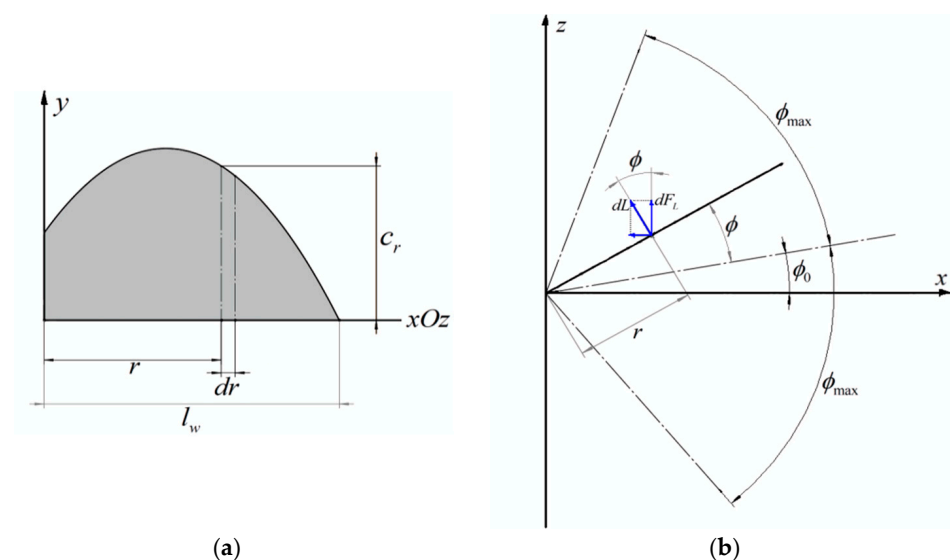


Figure 2. Simplified model of a rigid wing and its flapping motion: (a) simplified rigid wing model; (b) simplified flapping motion model.

The flapping-wing aircraft and its flapping motion are simplified. The body of the flapping-wing aircraft is simplified to a line segment coincident with the y -axis. The length of the line segment is meaningless, and the volume is not considered. The maximum wingspan l_w of the rigid wing is designed to be about 400 mm, and the maximum chord length is about 250 mm; the leading edge is approximately a straight line coincident with the x -axis. The trailing edge c_r is a function of r , approximately represented by a quadratic function (1), with the unit in m.

$$c_r = c_r(r) = -4.5r^2 + 1.485r + 0.126 \quad (1)$$

The flapping motion is simplified to a rigid body motion in which the leading edge of the wing oscillates back and forth around the y -axis in the plane xOy . Therefore, the flapping function is the function of the angle between the wing's leading edge and the

plane xOy changing over time, which is the function of the rotation angle ϕ of the wing around the y -axis at any time with respect to time t . To further simplify the calculation model, the original segmented flapping function is approximated as a sine function, and the expression of the flapping function within a period is given by Equation (2):

$$\phi = \phi(t) = \phi_{max} \sin(2\pi ft + \psi) + \phi_0 \quad (2)$$

where ϕ_{max} is the flapping amplitude with the unit in rad, f is the flapping frequency with the unit in Hz, and ϕ_0 is the mid-position angle with the unit in rad.

From the flapping function Equation (2), it can be seen that the flapping range of the wing is from $-\phi_{max} + \phi_0$ to $\phi_{max} + \phi_0$; at the middle position of the flapping motion, the angle between the wing and the plane xOy is ϕ_0 , which is called the mid-position angle in this paper.

Schenato and others [26] derived the lift and drag calculation formula for 3D translational flapping motion (3):

$$\begin{cases} L = \frac{1}{2} C_L \rho A U^2 \\ D = \frac{1}{2} C_D \rho A U^2 \end{cases} \quad (3)$$

where L is the lift with the unit in N, D is the drag with the unit in N, C_L is the lift coefficient without units, C_D is the drag coefficient without units, ρ is the air density with the unit in kg/m^3 , A is the area of the wing with the unit in m^2 , and U is the flapping speed with the unit in m/s .

According to the research of Dickinson, the lift coefficient and drag coefficient are functions of the angle of attack, and the empirical formula (4) is obtained:

$$\begin{cases} C_L = 0.225 + 1.58 \sin(2.13\alpha - 7.20) \\ C_D = 1.92 - 1.55 \cos(2.04\alpha - 9.82) \end{cases} \quad (4)$$

where α is the angle of attack with the unit in $^\circ$.

The angle of attack in the flapping motion usually changes periodically within a flapping period. To simplify the calculation, it is assumed that the angle of attack is constant at 15° during the downward stroke and 10° during the upward stroke. Then, according to the empirical formula (4), the lift coefficient is approximately as follows

$$\begin{cases} C_{Ld} = 0.9 \\ C_{Lu} = 0.6 \end{cases} \quad (5)$$

For a differential element of length dr , according to Equation (3), the lift L perpendicular to the wing plane produced by this differential element can be derived as shown in Equation (6), where the subscripts d and u represent the downstroke and upstroke processes, respectively.

$$\begin{cases} dL(t, r) = dL_d(t, r) - dL_u(t, r) \\ dL_d(t, r) = \frac{1}{2} \rho C_{Ld} U_d^2 c_r(t, r) dr \\ dL_u(t, r) = \frac{1}{2} \rho C_{Lu} U_u^2 c_r(t, r) dr \end{cases} \quad (6)$$

It is clear that even when simplified, the flapping motion cannot be equated to a straightforward translational movement of the wing. The flapping speed U continues to depend on both t and r . Sane and others [27] analyzed and believed that compared with the flapping speed, the influence of the aircraft's forward speed on force generation is secondary, and this view has been verified by experiments. Therefore, ignoring the forward speed of the aircraft, it can be considered that the flapping speed satisfies Equation (7):

$$U = U(t, r) = r\omega = r\dot{\phi}(t) \quad (7)$$

Taking the derivative of the flapping function equation, the angular velocity ω at any time can be obtained as Equation (8):

$$\omega = \frac{d\phi}{dt} = \dot{\phi}(t) = 2\pi f \phi_{max} \cos(2\pi f t + \psi) \quad (8)$$

Due to the wing being a rigid wing and undergoing rigid-body motion, meaning the leading and trailing edges of the airfoil do not change over time, the time-averaged function of the trailing edge is as shown in Equation (9).

$$\bar{c}_r(r) = c_r(r) = -4.5r^2 + 1.485r + 0.126 \quad (9)$$

Substituting Equation (7) into Equation (6) and then integrating it, the lift perpendicular to the wing plane during the downward and upward strokes is obtained as Equation (10):

$$\begin{cases} L_d(t) = \int_0^{l_w} dL_d(t, r) = \frac{1}{2} \rho C_{Ld} \dot{\phi}_d^2(t) \int_0^{l_w} r^2 \bar{c}_r(r) dr \\ L_u(t) = \int_0^{l_w} dL_u(t, r) = \frac{1}{2} \rho C_{Lu} \dot{\phi}_u^2(t) \int_0^{l_w} r^2 \bar{c}_r(r) dr \end{cases} \quad (10)$$

Substituting Equations (8) and (9) into Equation (10), Equation (11) is obtained:

$$\begin{cases} L_d(t) = \left[2\rho C_{Ld} \pi^2 f^2 \phi_{max}^2 \int_0^{l_w} r^2 \bar{c}_r(r) dr \right] \cdot \cos^2(2\pi f t + \psi) \\ L_u(t) = \left[2\rho C_{Lu} \pi^2 f^2 \phi_{max}^2 \int_0^{l_w} r^2 \bar{c}_r(r) dr \right] \cdot \cos^2(2\pi f t + \psi) \end{cases} \quad (11)$$

Then, the average lift calculation formula perpendicular to the wing plane is derived as in Equation (12):

$$\begin{cases} \bar{L}_d = f \int_0^{\frac{1}{f}} L_d(t) dt = 4\rho C_{Ld} \pi^3 f^4 \phi_{max}^2 \int_0^{l_w} r^2 \bar{c}_r(r) dr \\ \bar{L}_u = f \int_0^{\frac{1}{f}} L_u(t) dt = 4\rho C_{Lu} \pi^3 f^4 \phi_{max}^2 \int_0^{l_w} r^2 \bar{c}_r(r) dr \end{cases} \quad (12)$$

Further, the lift calculation formula in the vertical direction F_L is derived as in Equation (13):

$$\begin{cases} \bar{F}_{Ld} = \frac{1}{2\phi_{max}} \int_{-\phi_{max}+\phi_0}^{\phi_{max}+\phi_0} \bar{L}_d \cos\phi d\phi = \frac{\bar{L}_d}{2\phi_{max}} \int_{-\phi_{max}+\phi_0}^{\phi_{max}+\phi_0} \cos\phi d\phi \\ \bar{F}_{Lu} = \frac{1}{2\phi_{max}} \int_{-\phi_{max}+\phi_0}^{\phi_{max}+\phi_0} \bar{L}_u \cos\phi d\phi = \frac{\bar{L}_u}{2\phi_{max}} \int_{-\phi_{max}+\phi_0}^{\phi_{max}+\phi_0} \cos\phi d\phi \end{cases} \quad (13)$$

Finally, the lift difference generated by the upward and downward strokes within a period is in Equation (14):

$$\bar{F}_L = \bar{F}_{Ld} - \bar{F}_{Lu} = 4\rho(C_{Ld} - C_{Lu})\pi^3 f^4 \phi_{max} \sin\phi_{max} \cos\phi_0 \int_0^{l_w} r^2 \bar{c}_r(r) dr \quad (14)$$

Analyzing Equation (14), the air density $\rho = 1.29 \text{ kg/m}^3$ at room temperature, which is a constant. In the simplified model, it is assumed that $C_{Ld} = 0.9$ and $C_{Lu} = 0.6$ are constants; in the simplified model, it is assumed that the shape of the wing remains unchanged, then the definite integral $\int_0^{l_w} r^2 \bar{c}_r(r) dr$ is a constant. In summary, the variables affecting the average lift include f , ϕ_{max} and ϕ_0 , which are all parameters of the flapping function.

f is the flapping frequency, and its value range is $f \in [0, +\infty)$. ϕ_{max} is the flapping amplitude, and ϕ_0 is the mid-position angle; its value typically satisfies $-\frac{\pi}{2} \leq -\phi_{max} + \phi_0 \leq 0 \leq \phi_{max} + \phi_0 \leq \frac{\pi}{2}$. Usually, ϕ_0 is not too large, and it can be considered that its value range is $\phi_0 \in [-\frac{\pi}{18}, \frac{\pi}{18}]$. Therefore, it can be considered that the value range of flapping amplitude is $\phi_{max} \in [0, \frac{\pi}{2}]$. The relationship between the three and the average lift is shown in Table 1. In short, the larger f is, the larger ϕ_{max} is, and the smaller $|\phi_0|$ is, the larger $\bar{F}_L$ will be.

Table 1. Analysis of key parameters.

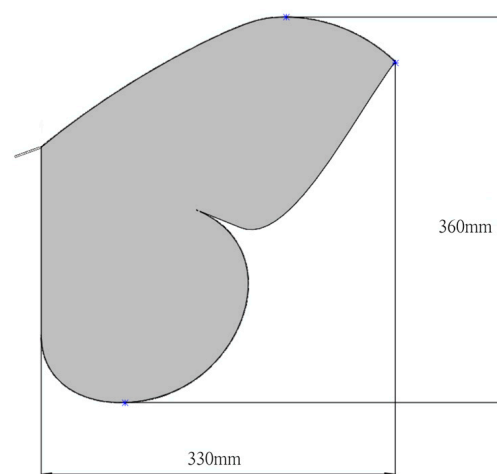
Changing Parameter	Value Range	Relationship with Average Lift	Conclusion
f	$[0, +\infty)$	$\bar{F}_L \propto f^4$	The larger f is, the larger $\bar{F}_L$ will be
ϕ_{max}	$[0, \pi/2]$	$\bar{F}_L \propto \phi \sin \phi_{max_{max}}$	The larger ϕ_{max} is, the larger $\bar{F}_L$ will be
ϕ_0	$[-\pi/18, \pi/18]$	$\bar{F}_L \propto \cos \phi_0$	The larger $ \phi_0 $ is, the smaller $\bar{F}_L$ will be

Further analysis can be seen that ϕ_{max} and f have a more significant impact on $\bar{F}_L$, while ϕ_0 does not have a significant impact on $\bar{F}_L$. At the same time, in this calculation model, it is assumed that C_{Ld} and C_{Lu} are constants, but in actual conditions, this is not the case. The change in ϕ_0 will cause a change in the angle of attack and then affect C_{Ld} and C_{Lu} . Therefore, the impact of the mid-position angle on lift needs to be further explored in the subsequent simulation and experiment.

3.2. Simulation of the Impact of Key Parameters on the Performance of Flapping-Wing Aircraft

Through the simplified kinematic modeling analysis, it can be seen that the flapping function has three controllable parameters: flapping amplitude, flapping frequency, and mid-position angle. According to the mathematical modeling analysis, the lift generated by the flapping motion is positively correlated with ϕ_{max} and f , and negatively correlated with $|\phi_0|$. The following will use the XFlow software for simulation calculation to verify the analysis results. Simulation calculations will be performed from five angles: the impact of flapping amplitude ϕ_{max} , flapping frequency f , and mid-position angle ϕ_0 on aerodynamic characteristics. It will further delve into how the quick return feature affects the aerodynamic properties at various flapping frequencies f . It will further explore the steering capabilities influenced by the differential flapping amplitude between the left and right wings, focusing on the wing's flapping amplitude ϕ_{max} .

Firstly, a simple 3D model of the flapping-wing aircraft is completed. A rigid wing with a unilateral wingspan of about 330 mm and a maximum chord length of about 360 mm is designed, as shown in Figure 3. The left and right wings are driven by the left and right servos, respectively. The output shaft of the servo is at a 15° angle with the centerline of the flapping-wing aircraft so that the wing has a certain rotation during flapping, as shown in Figure 4b, with the black wing representing the ventral surface of the wing.

**Figure 3.** Dimensions of Rigid wing. The blue * represents the measurement point.

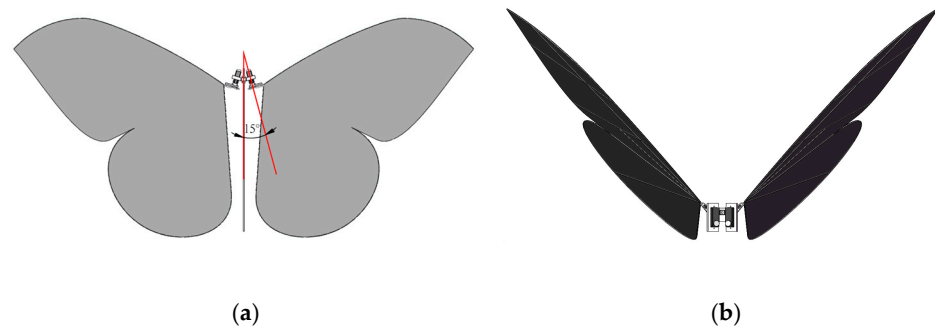


Figure 4. Flapping-wing aircraft. (a) top view of the wings laid flat; (b) front view at the end of the upward stroke.

In the XFlow software, a 3D virtual wind tunnel is built as an aerodynamic simulation platform, and the parameter settings are shown in Table 2. The simplified 3D model of the flapping-wing aircraft is imported into the virtual wind tunnel. The main body of the flapping-wing aircraft is fixed, and the centerline is located in the virtual wind tunnel plane xOz . The angle between the centerline and the wind tunnel x -axis is called the pitch angle, and the default pitch angle is 10° . The left and right wings make rigid body motions and oscillate periodically around the output shaft of the left and right servos.

Table 2. Virtual wind tunnel parameter settings.

Parameter Name	Parameter Description	Parameter Value
Calculation Region	Virtual wind tunnel	Cuboid $3\text{ m} \times 1.5\text{ m} \times 1.5\text{ m}$ Molecular Weight $MW = 28.996\text{ u}$
Fluid	Air	Density $\rho = 1.225\text{ kg}\cdot\text{m}^{-3}$ Working Temperature $T = 28.15\text{ K}$ Dynamic Viscosity $\mu = 1.7894 \times 10^{-5}\text{ Pa}\cdot\text{s}$
Inlet	Upstream direction	Inlet Velocity $V_x = 3\text{ m}\cdot\text{s}^{-1}$, $V_y = 0$, $V_z = 0$
Outlet	Pressure boundary	Relative Inlet Pressure $P_{out} = 0$

The periodic reciprocating flapping motion of the wing is controlled by setting the function of the angle of rotation of the wing around its own x -axis, which corresponds to the output shaft of the servo over time. This function is the flapping function. The flapping function inspired by the flapping behavior of *Lepidoptera* insects is shown in Equation (15), which is composed of two segmented sine functions smoothly connected.

$$\phi = \phi(t') = \begin{cases} -\phi_{\max} \sin\left(\frac{t' \times \pi}{T_1} + \varphi_1\right) & 0 \leq t' < T_1 \\ -\phi_{\max} \sin\left(\frac{t' \times \pi}{T_2} + \varphi_2\right) & T_1 \leq t' < T \end{cases} \quad (15)$$

where $\phi_{\max}$ is the flapping amplitude parameter, which is half of the angle between the wing position at the end of the upward and downward strokes; T_1 and T_2 are period parameters, controlling the periods of the two segmented periodic functions; φ_1 and φ_2 are phase parameters used to smoothly connect the two segmented functions; ϕ_0 is the mid-position angle; t' is the function of time t , which can be obtained through floor division operation, as shown in Equation (16).

$$t' = t'(t) = t - \left\lfloor \frac{t}{T} \right\rfloor \times T \quad (16)$$

where t is the simulation running time; T is the flapping period.

3.2.1. Impact of Quick Return Feature of Flapping Motion on Lift

In Section 3.1, it is assumed that the upward and downward strokes occur at the same frequency. However, in fact, as can be seen from the lift calculation formula, the greater the difference in flapping speed between the upward and downward strokes, the greater the average lift generated. The quick return feature of the flapping motion will increase the difference in flapping speed. To qualitatively explore the impact of the quick return feature on aerodynamic performance, three groups of flapping functions are designed, simulated, and calculated. The control parameters of the right-wing flapping function are shown in Table 3, and the left-wing flapping function is opposite to the right wing.

Table 3. Control parameters of flapping motion with different quick return features.

Parameter	Flapping Motion without Quick Return Feature	Flapping Motion with Quick Upward Strokes	Flapping Motion with Quick Downward Strokes
ϕ_{max}	$2\pi/9$	$2\pi/9$	$2\pi/9$
T_1	0.125	0.1	0.15
T_2	0.125	0.15	0.1
φ_1	$\pi/2$	$\pi/2$	$\pi/2$
φ_2	$\pi/2$	$5\pi/6$	0
ϕ_0	$\pi/18$	$\pi/18$	$\pi/18$
T	0.25	0.25	0.25

The simulation time is set to 1 s, including four flapping cycles. The simulation data is imported into the software Origin, and the lift curves of the three flapping motions over time are drawn, as shown in Figure 5. It can be seen that the quick return feature of flapping motion has a significant impact on aerodynamic performance. The average lift within a period is calculated (0.25 s–0.5 s). The average lift generated by the flapping motion without a quick return feature within a period is about 0.670 N. The average lift by the flapping motion with a quick upward stroke is about 0.505 N; the average lift by the flapping motion with a quick downward stroke is about 0.782 N. Therefore, it can be concluded that the quick downward feature can significantly improve the aerodynamic performance of the flapping motion.

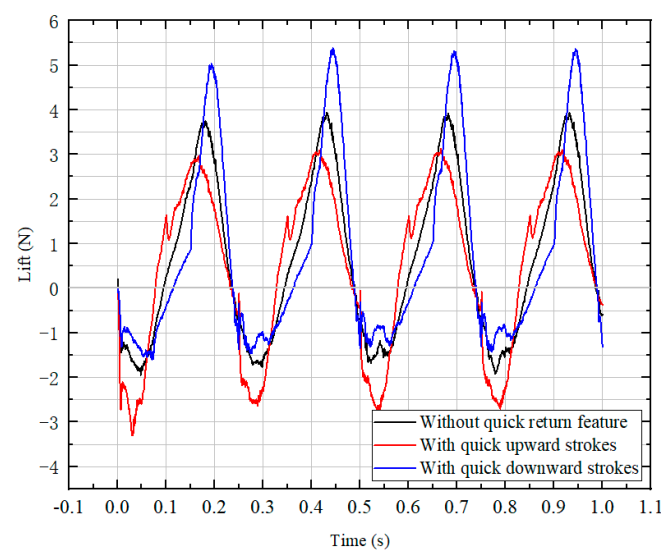


Figure 5. The impact of the flapping quick return feature on lift.

3.2.2. Impact of Flapping Amplitude of Flapping Motion on Lift

As can be seen from the lift calculation formula, under the same flapping frequency and mid-position angle conditions, the larger the flapping amplitude, the greater the lift

generated. Three groups of flapping functions are designed, simulated, and calculated to verify the impact of flapping amplitude on aerodynamic performance. The control parameters of the right-wing flapping function are shown in Table 4, and the left-wing flapping function is opposite to the right wing.

Table 4. Control parameters of flapping motion with different flapping amplitude.

Parameter	Flapping Motion with a 30° Flapping Amplitude	Flapping Motion with a 40° Flapping Amplitude	Flapping Motion with a 50° Flapping Amplitude
ϕ_{max}	$\pi/6$	$2\pi/9$	$5\pi/18$
T_1	0.15	0.15	0.15
T_2	0.1	0.1	0.1
φ_1	$\pi/2$	$\pi/2$	$\pi/2$
φ_2	0	0	0
ϕ_0	$\pi/18$	$\pi/18$	$\pi/18$
T	0.25	0.25	0.25

The simulation time is set to 1 s, including four flapping cycles. The simulation data is imported into the software Origin, and the lift curves of the three flapping motions over time are drawn, as shown in Figure 6. It can be seen that the amplitude of flapping motion has a significant impact on aerodynamic performance. The average lift within a period was calculated (0.25 s–0.5 s). The average lift generated by the flapping motion with a flapping amplitude of 30° within a period is about 0.737 N. The average lift of the flapping motion with a flapping amplitude of 40° is about 0.782 N; the average lift of the flapping motion with a flapping amplitude of 50° is about 0.864 N. Therefore, it can be concluded that increasing the flapping amplitude can improve the aerodynamic performance of the flapping motion. This is consistent with the results of mathematical modeling analysis.

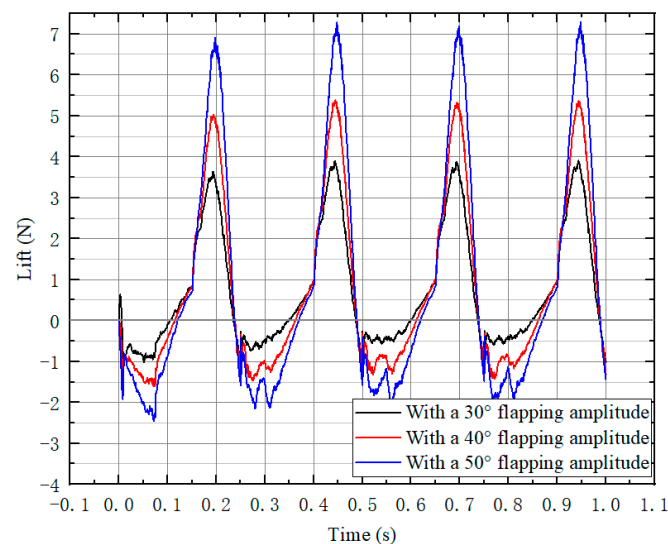


Figure 6. The impact of flapping amplitude on lift.

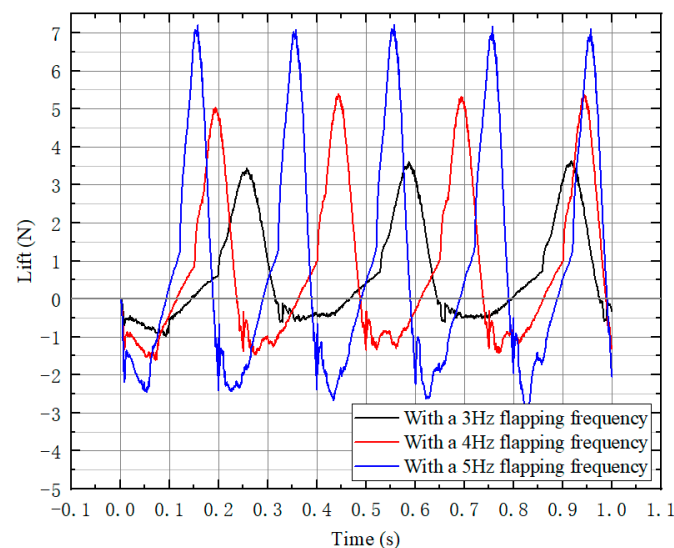
3.2.3. Impact of Flapping Frequency of Flapping Function on Lift

As can be seen from the lift calculation formula, under the same flapping amplitude and mid-position angle conditions, the greater the flapping frequency, the greater the lift generated. To verify the impact of flapping frequency on aerodynamic performance, three groups of flapping functions are designed, simulated, and calculated. The control parameters of the right-wing flapping function are shown in Table 5, and the left-wing flapping function is opposite to the right wing.

Table 5. Control parameters of flapping motion with different flapping frequencies.

Parameter	Flapping Motion with a 3 Hz Flapping Frequency	Flapping Motion with a 4 Hz Flapping Frequency	Flapping Motion with a 5 Hz Flapping Frequency
ϕ_{max}	$2\pi/9$	$2\pi/9$	$2\pi/9$
T_1	0.198	0.15	0.12
T_2	0.132	0.1	0.08
φ_1	$\pi/2$	$\pi/2$	$\pi/2$
φ_2	0	0	0
ϕ_0	$\pi/18$	$\pi/18$	$\pi/18$
T	0.33	0.25	0.2

The simulation time is set to 1 s, including 3–5 flapping cycles. The simulation data is imported into the software Origin_2021, and the lift curves of the three flapping motions over time are drawn, as shown in Figure 7. It can be seen that the frequency of flapping motion has a significant impact on aerodynamic performance. The average lift within a period is calculated (all in the second flapping cycle). The average lift generated by the flapping motion with a flapping frequency of 3 Hz within a period is about 0.674 N. The average lift of the flapping motion with a flapping frequency of 4 Hz is about 0.782 N; the average lift of the flapping motion with a flapping frequency of 5 Hz is about 0.836 N. Therefore, it can be concluded that increasing the flapping frequency can improve the aerodynamic performance of the flapping motion. This is consistent with the results of mathematical modeling analysis.

**Figure 7.** The impact of flapping frequency on lift.

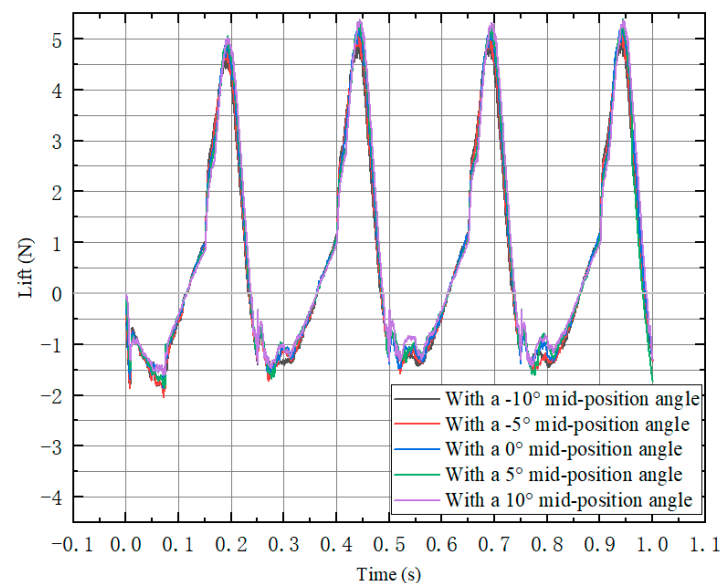
3.2.4. Impact of Mid-Position Angle of Flapping Function on Lift

As can be seen from the lift calculation formula, under the same flapping amplitude and flapping frequency conditions, the greater the absolute value of the mid-position angle, the smaller the lift generated. However, the change of mid-position angle may cause a change in the angle of attack, thereby changing the lift coefficient and then affecting the aerodynamic performance. To qualitatively explore the impact of mid-position angle on aerodynamic performance, five groups of flapping functions are designed, simulated, and calculated. The control parameters of the right-wing flapping function are shown in Table 6, and the left-wing flapping function is opposite to the right wing.

Table 6. Control parameters of flapping motion with different mid-position angles.

Parameter	Mid-Position Angle of -10°	Mid-Position Angle of -5°	Mid-Position Angle of 0°	Mid-Position Angle of 5°	Mid-Position Angle of 10°
ϕ_{max}	$2\pi/9$	$2\pi/9$	$2\pi/9$	$2\pi/9$	$2\pi/9$
T_1	0.15	0.15	0.15	0.15	0.15
T_2	0.1	0.1	0.1	0.1	0.1
φ_1	$\pi/2$	$\pi/2$	$\pi/2$	$\pi/2$	$\pi/2$
φ_2	0	0	0	0	0
ϕ_0	$-\pi/18$	$-\pi/36$	0	$\pi/36$	$\pi/18$
T	0.25	0.25	0.25	0.25	0.25

The simulation time is set to 1 s, including four flapping cycles. The simulation data is imported into the software Origin, and the lift curves of the five flapping motions over time are drawn, as shown in Figure 8. It can be seen that the mid-position angle of flapping motion has an unremarkable impact on aerodynamic performance. The average lift within a period is calculated (0.25 s–0.5 s). The average lift generated by the flapping motion with a mid-position angle of -10° within a period is about 0.609 N. The average lift of the flapping motion with a mid-position angle of -5° is about 0.653 N. The average lift of the flapping motion with a mid-position angle of 0° is about 0.715 N. The average lift of the flapping motion with a mid-position angle of 5° is about 0.741 N, and the average lift of the flapping motion with a mid-position angle of 10° is about 0.782 N. Therefore, it can be concluded that increasing the mid-position angle can slightly improve the aerodynamic performance. This is slightly different from the results of mathematical modeling analysis.

**Figure 8.** The impact of mid-position angle on lift.

The difference between the results of simulation calculation analysis and mathematical modeling analysis is that the former shows that the larger the mid-position angle, the greater the average lift, while the latter shows that the larger the absolute value of the mid-position angle, the smaller the average lift. The similarity is that the change of mid-position angle has an insignificant impact on the average lift. It is speculated that this is because the impact of the mid-position angle on the angle of attack is ignored when mathematical modeling is carried out, resulting in an imperfect calculation model. In the lift calculation formula for flapping-wing motion, C_{Ld} and C_{Lu} are periodically varying, and the mid-position angle may affect this variation. However, to simplify the calculation, in the computational model, we set both as constants. This may be the reason for the

difference between the conclusions of the computational model and the simulation results. The specific impact of mid-position angle on flapping motion needs to be further studied during the flight experiment of the biomimetic flapping-wing aircraft.

3.2.5. Impact of Difference in Flapping Amplitude of Left and Right Wings on Turning

The biomimetic flapping-wing aircraft designed in this paper does not have a tail rudder to control turning, and it is planned to achieve turning function by creating a difference in the flapping amplitude of the left and right wings. To qualitatively explore whether creating a difference in the flapping amplitude of the left and right wings can achieve the turning function of the aircraft, a group of flapping functions is designed, simulated, and calculated. The control parameters of the left and right wings flapping functions are shown in Table 7.

Table 7. Control parameters of flapping motion with amplitude difference for turning.

Parameter	Flapping Motion with a 30° Flapping Amplitude	Flapping Motion with a 40° Flapping Amplitude
ϕ_{max}	$-5\pi/18$	$\pi/6$
T_1	0.15	0.15
T_2	0.1	0.1
φ_1	$\pi/2$	$\pi/2$
φ_2	0	0
ϕ_0	$-\pi/18$	$\pi/18$
T	0.25	0.25

The simulation time is set to 1 s, including four flapping cycles. The simulation data is imported into the software Origin and the curve of the overall torque of the aircraft around the y -axis over time is drawn, as shown in Figure 9. The torque is the counterclockwise torque, which causes the aircraft to turn left when it is positive.

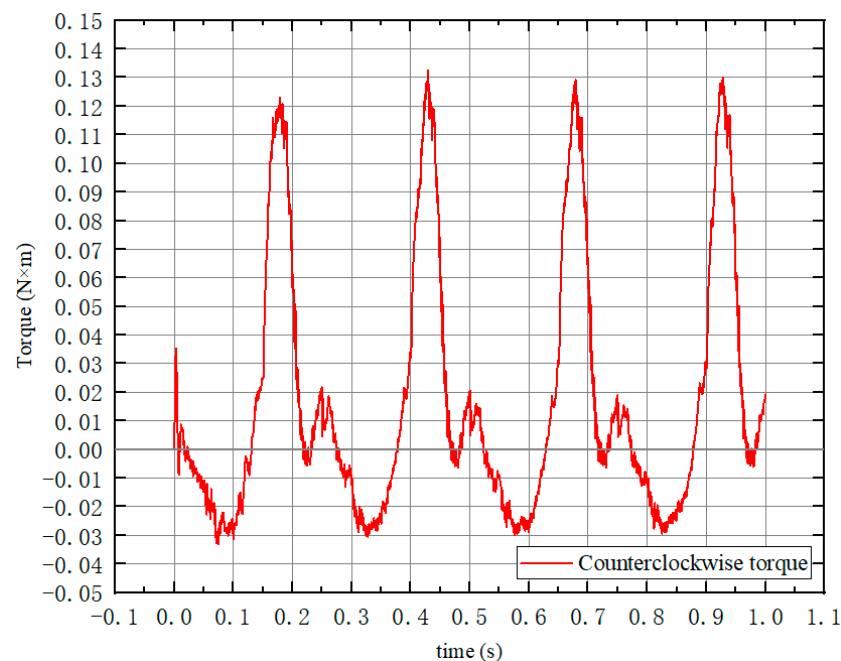


Figure 9. Torque change curve generated by amplitude difference.

Using the simulation data, the average torque within a period (0.25 s–0.5 s) is calculated to be 0.017 N·m; that is, increasing the flapping amplitude of the left-wing and decreasing the flapping amplitude of the right wing can achieve the left turn of the aircraft. This

conclusion is contrary to subjective cognition, and whether this conclusion is correct needs to be verified by the flight test of the aircraft.

4. Flight Experiment and Result Analysis of Biomimetic Flapping-Wing Aircraft

4.1. Design and Manufacture of Biomimetic Flapping-Wing Aircraft

Referring to the results of the simulation calculation, a pair of wings with a unilateral wingspan of about 330 mm and a maximum chord length of about 360 mm can generate about 0.6 N to 0.8 N of lift, which means it can drive a flapping-wing aircraft with a weight of about 60 g to 80 g to fly. Therefore, the flapping-wing aircraft needs to be designed as lightweight as possible.

Referring to the previous biomimetic analysis, the wings of the biomimetic flapping-wing aircraft are designed as a lightweight biomimetic flexible membrane wing structure. The veins are carbon fiber rods of different diameters bonded according to a certain venation, and the wing membranes are lightweight film materials adhered to the carbon fiber skeleton. The two wings are directly driven by the left and right servos fixed on the servo frame. The servo bracket, control board bracket, hind-wing bracket, and battery bracket are installed on the main carbon fiber square rod, as shown in Figure 10. The wing shape and wingspan of the flapping-wing aircraft are the same as those of the model used in the simulation, as shown in Figures 3 and 4. The flapping-wing aircraft, including the control board, battery, and wires, weighs 66.5 g.

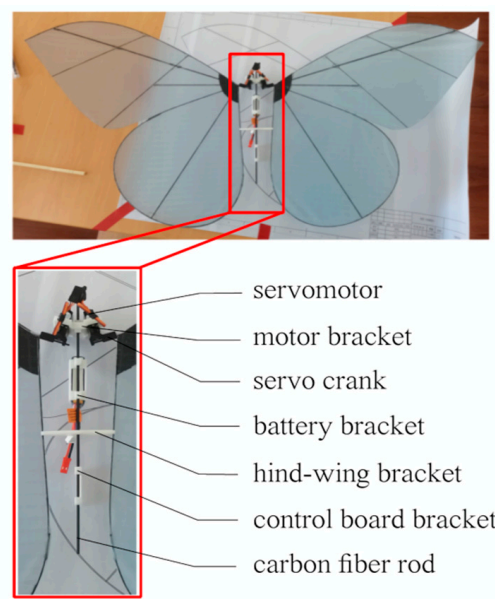


Figure 10. Overall Top View of Biomimetic Flapping-wing Aircraft.

For flight control, a custom Arduino control board is selected, the 8-channel pulse position modulation (PPM) signal is received by the A8S signal receiver (FLYSKY, Guangdong, China), and the control signal is provided by the FS-i6X panel flight controller (FLYSKY, Guangdong, China). The left and right servos output torque periodically according to the flapping function and directly drive the left and right wings, as shown in Figure 11. The selected servo motor is the GDW1906B servo (Dongguan City Gliding World Electronic Technology Co., Ltd, Dongguan City, China), which can generate approximately $2.6 \text{ kg} \times \text{cm}$ of torque when driven by a 7 V DC power supply. The flight controller changes the key parameters of the flapping function through different joysticks or buttons, thereby realizing the control of the flapping-wing aircraft.

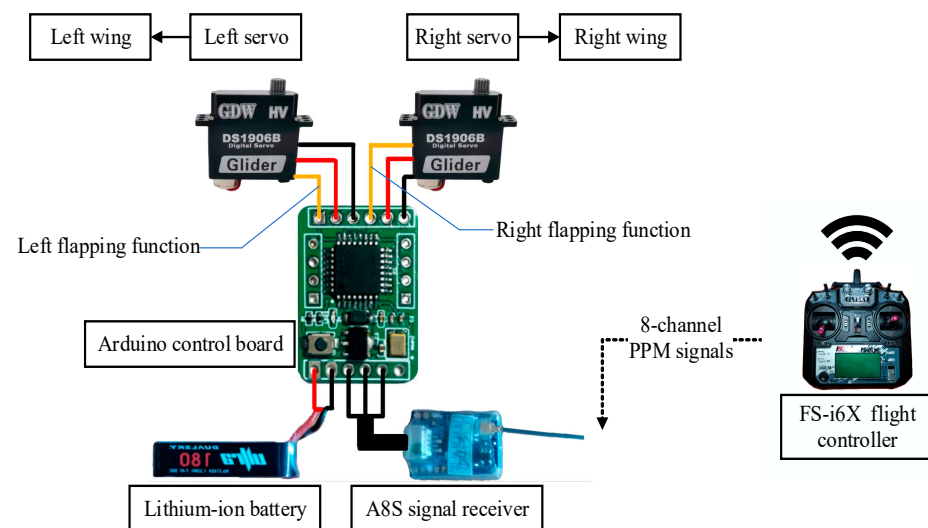


Figure 11. Flight Control Architecture.

4.2. Experiment Scheme and Process

In Section 3, a virtual wind tunnel simulation calculation platform was built to qualitatively study the impact of flapping parameters on the aerodynamic performance of flapping-wing aircraft. In this chapter, the biomimetic flapping-wing aircraft will be flight-tested to verify the accuracy of the simulation results.

Through mathematical modeling and simulation calculation analysis, it can be seen that flapping amplitude and flapping frequency are the key influencing factors of lift generation of flapping motion, while the impact of mid-position angle on lift is not clear and needs further study. Therefore, the experiment will be divided into three parts: lift test, turning test, and flight altitude test.

For flapping amplitude, a lift test is designed to explore its impact on the flight capability of the flapping-wing aircraft, and a turning test is designed to explore its impact on the amplitude difference turning capability. For flapping frequency, only a lift test is designed to explore its impact on the flight capability of the flapping-wing aircraft. For the mid-position angle, a lift test is designed to explore its impact on the flight capability of the flapping-wing aircraft, and at the same time, a flight altitude test is designed to explore the impact of the change of the absolute value of the mid-position angle during flight on the flight capability. The experiment process is shown in Figure 12.

The experimental scheme is designed as follows:

- (1) **Experimental Site:** The authors of [28] point out that gusts, or sudden changes in wind speed, can exert a certain influence on aspects such as the aircraft's attitude control. In fact, the flapping-wing aircraft prototype is greatly affected by natural wind, so an indoor environment with almost no wind is chosen as the experimental site. In addition, since the controller and the aircraft communicate wirelessly, it is necessary to ensure there is no electromagnetic interference. Ultimately, we chose a square indoor space measuring 12 m in both the x -axis and y -axis directions, which were windless and free from electromagnetic interference. The flapping-wing aircraft was released at a height of approximately 1.8 m above the ground;
- (2) **Experimental Content:** The experiment will primarily consist of three sections: lift test, turning test, and flight altitude test. The lift test explores the impact of flapping amplitude, flapping frequency, and mid-position angle on the aircraft's flight capability; the turning test explores the amplitude difference turning capability; and the flight altitude test explores the control of the flight altitude of the flapping-wing aircraft;

- (3) **Experimental Recording Method:** The flapping-wing aircraft is not equipped with sensors related to aerodynamics, and the flight capability of the flapping-wing aircraft is challenging to quantify. The experimental process will use video recording, with the camera placed on a fixed tripod for a fixed shooting position;
- (4) **Data Analysis:** The position of the flapping-wing aircraft every 0.1 s in the experimental video is superimposed on the same negative, and a Bézier curve is drawn to plot the flight trajectory of the flapping-wing aircraft, then the flight capability of the flapping-wing aircraft is evaluated;
- (5) **Benchmark Parameters:** A large number of flight tests have shown that when the flapping amplitude is about 54° , the flapping frequency is about 4 Hz, the mid-position angle is about 5° , and the initial pitch angle is about 10° , the flapping-wing aircraft has excellent flight performance. Therefore, the flight experiment will take these parameters as the benchmark parameter, and on this basis, the parameters will be changed, and the impact of each parameter on the flight performance will be analyzed.

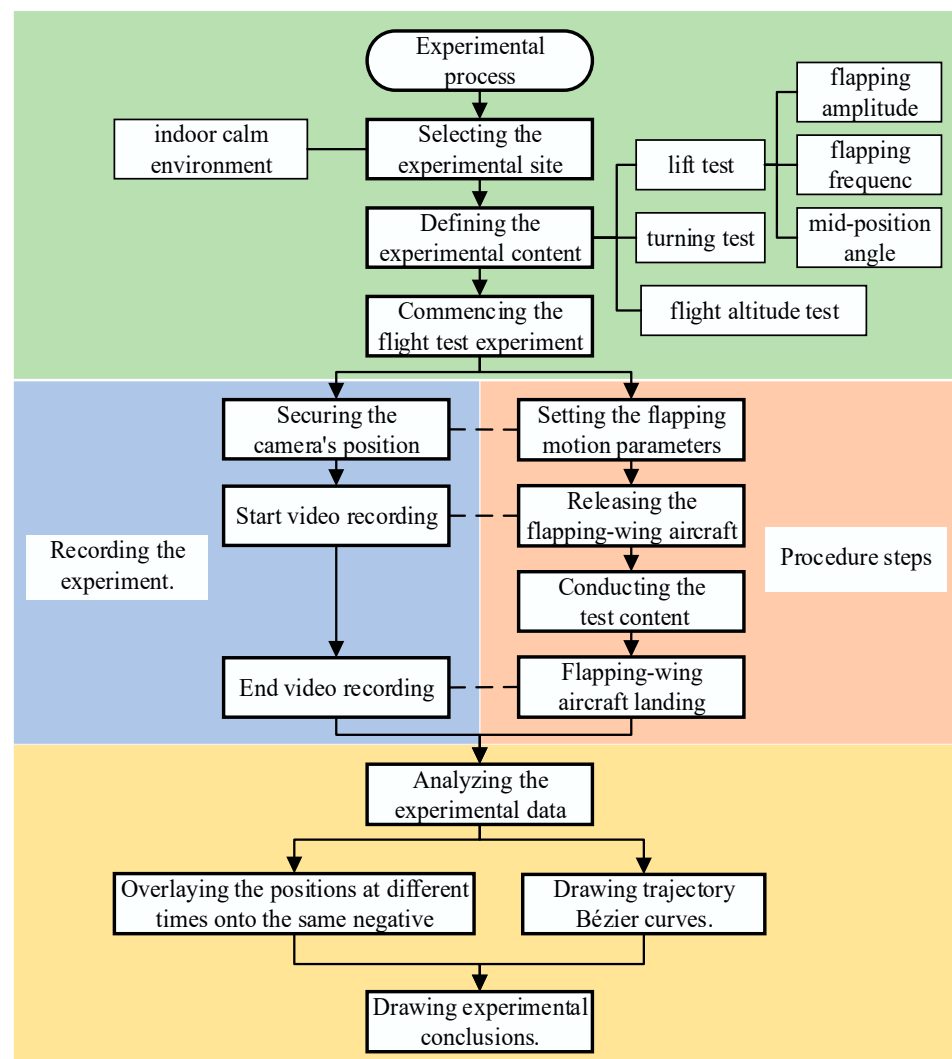


Figure 12. Flight Experiment Process Diagram.

4.3. Lift Test

4.3.1. Experiment 1: Impact of Flapping Amplitude on Flight Capability of Flapping-Wing Aircraft

Three flight tests were carried out using the flight controller to input parameters, as shown in Table 8.

Table 8. Control parameter table of experiment 1.

Control Parameters	(a)	(b)	(c)
Flapping frequency	4 Hz	4 Hz	4 Hz
Mid-position angle	5°	5°	5°
Flapping-wing aircraft	54°	45°	36°
Initial pitch angle	10°	10°	10°

The experimental results are shown in Figure 13.

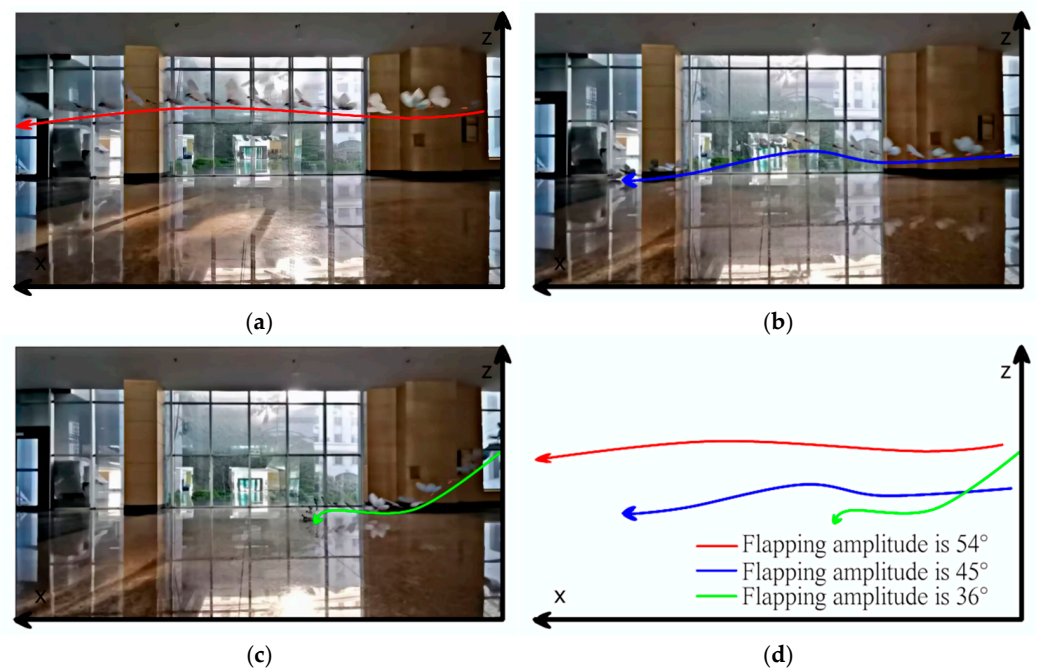


Figure 13. Results of Experiment 1 in Lift Test. (a) diagram with a 54° flapping amplitude; (b) diagram with a 45° flapping amplitude; (c) diagram with a 36° flapping amplitude; (d) Merged diagram of flight trajectories.

When the flapping amplitude is 54°, the flight trajectory of the flapping-wing aircraft is horizontal, indicating that it generates sufficient and stable lift. The position of the flapping-wing aircraft is evenly distributed and scattered over time, indicating that it generates a large propulsive force. In general, with a flapping amplitude of around 54°, the flapping-wing aircraft exhibits robust flight capabilities.

When the flapping amplitude is 45°, the flight trajectory of the flapping-wing aircraft slopes downward after fluctuating, indicating that the generated lift is just not enough to overcome its own weight and cannot fly stably. The position of the flapping-wing aircraft is evenly distributed and scattered over time, indicating that it generates a large propulsive force. In general, with a flapping amplitude of around 45°, the flapping-wing aircraft exhibits subpar flight capabilities.

When the flapping amplitude is 36°, the flight trajectory of the flapping-wing aircraft slopes downward severely, indicating that the generated lift is seriously insufficient. The severe downward slope of the flight trajectory indicates that the position distribution of the flapping-wing aircraft over time does not signify the generation of propulsive force but merely indicates that the generated lift is insufficient to mitigate its descent rate. In general, with a flapping amplitude of around 36°, the flapping-wing aircraft exhibits extremely subpar flight capabilities.

In summary, the amplitude of flapping motion impacts the flight capability of the flapping-wing aircraft, and increasing the flapping amplitude can enable the aircraft to

obtain better flight performance. This is consistent with the results of the simulation calculation, indicating that the simulation results are basically accurate.

4.3.2. Experiment 2: Impact of Flapping Frequency on Flight Capability of Flapping-Wing Aircraft

Two flight tests were carried out using the flight controller to input parameters, as shown in Table 9.

Table 9. Control parameter table of experiment 2.

Control Parameters	(a)	(b)
Flapping frequency	4 Hz	3.5 Hz
Mid-position angle	5°	5°
Flapping-wing aircraft	54°	54°
Initial pitch angle	10°	10°

The experimental results are shown in Figure 14.

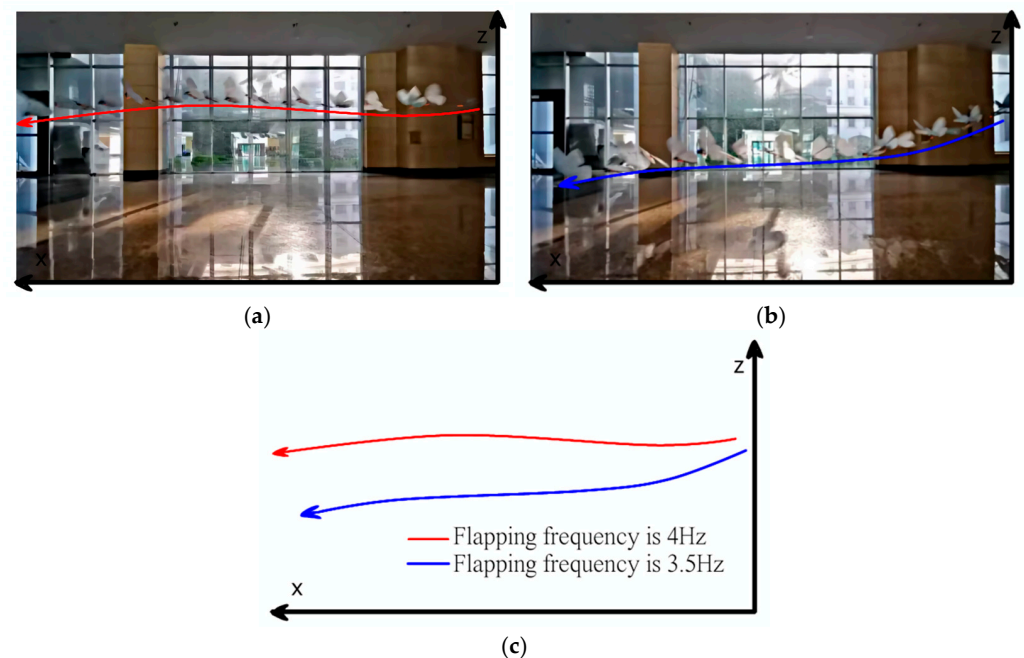


Figure 14. Results of Experiment 2 in Lift Test. (a) diagram with a 4 Hz flapping frequency; (b) diagram with a 3.5 Hz flapping frequency; (c) merged diagram of flight trajectories.

When the flapping frequency is 4 Hz, the flight trajectory of the flapping-wing aircraft is horizontal, indicating that it generates sufficient and stable lift. The position of the flapping-wing aircraft is evenly distributed and scattered over time, indicating that it generates a large propulsive force. In general, with a flapping frequency of around 4 Hz, the flapping-wing aircraft exhibits robust flight capabilities.

When the flapping frequency is 3.5 Hz, the flight trajectory of the flapping-wing aircraft is horizontal after fluctuating, indicating that the generated lift can just overcome its own weight and fly stably. The position of the flapping-wing aircraft is evenly distributed and scattered over time, indicating that it generates a large propulsive force. In general, with a flapping frequency of around 3.5 Hz, the flapping-wing aircraft exhibits average flight capabilities.

In summary, the frequency of flapping motion has an impact on the flight capability of the flapping-wing aircraft, and increasing the flapping frequency can enable the aircraft to

obtain better flight performance. This is consistent with the simulation calculation results, indicating that the results are basically accurate.

4.3.3. Experiment 3: Impact of Mid-Position Angle of Flapping Motion on Flight Capability of Flapping-Wing Aircraft

Three flight tests were carried out using the flight controller to input parameters, as shown in Table 10.

Table 10. Control parameter table of experiment 3.

Control Parameters	(a)	(b)	(c)
Flapping frequency	4 Hz	4 Hz	4 Hz
Mid-position angle	5°	0°	−5°
Flapping-wing aircraft	54°	54°	54°
Initial pitch angle	10°	10°	10°

The experimental results are shown in Figure 15.

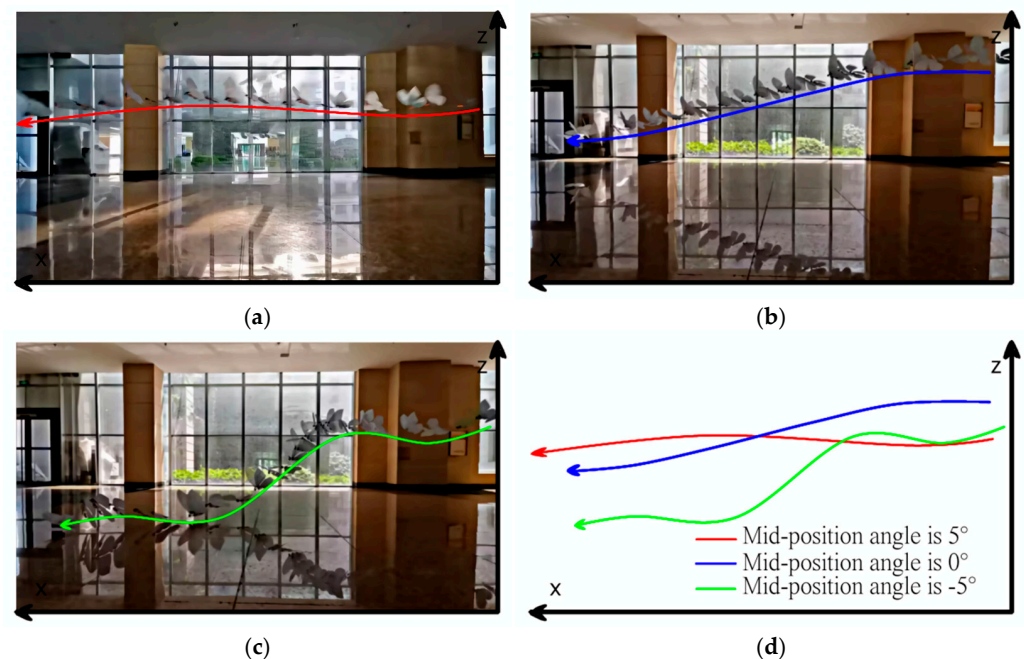


Figure 15. Results of Experiment 3 in Lift Test. (a) diagram with a 5° mid-position angle; (b) diagram with a 0° mid-position angle; (c) diagram with a −5° mid-position angle; (d) merged diagram of flight trajectories.

When the mid-position angle is 5°, the flight trajectory of the flapping-wing aircraft is horizontal, indicating that it generates sufficient and stable lift. The position of the flapping-wing aircraft is evenly distributed and scattered over time, indicating that it generates a large propulsive force. In general, with a mid-position angle of around 5°, the flapping-wing aircraft exhibits robust flight capabilities.

When the mid-position angle is 0°, the flight trajectory of the flapping-wing aircraft slopes downward slightly, indicating that the generated lift is basically sufficient and stable. The position of the flapping-wing aircraft is unevenly distributed over time, indicating that the generated propulsive force is unstable. In general, with a mid-position angle of around 0°, the flapping-wing aircraft exhibits fair flight capabilities.

When the mid-position angle is −5°, the flight trajectory of the flapping-wing aircraft slopes downward severely after fluctuating, indicating that the generated lift is insufficient. The severe downward slope of the flight trajectory indicates that the position distribution

of the flapping-wing aircraft over time does not signify the generation of propulsive force but merely indicates that the generated lift is sufficient to mitigate its descent rate. In general, with a mid-position angle of around -5° , the flapping-wing aircraft exhibits subpar flight capabilities.

In summary, the mid-position angle of flapping motion has an impact on the flight capability of the flapping-wing aircraft, and appropriately increasing the mid-position angle can enable the aircraft to obtain better flight performance. This is consistent with the results of the simulation calculation, indicating that the simulation results are basically accurate.

4.4. Turning Test: Turning Based on Amplitude Difference of Left and Right Wings

Two flight tests were carried out using the flight controller to input parameters, as shown in Table 11.

Table 11. Control parameter table of turning test.

Control Parameters	(a)	(b)
Flapping frequency	4 Hz	4 Hz
Mid-position angle	5°	5°
Left flapping-wing aircraft	58.5°	63°
Right flapping-wing aircraft	49.5°	45°
Amplitude difference	9°	18°
Initial pitch angle	10°	10°

The experimental results are shown in Figure 16.

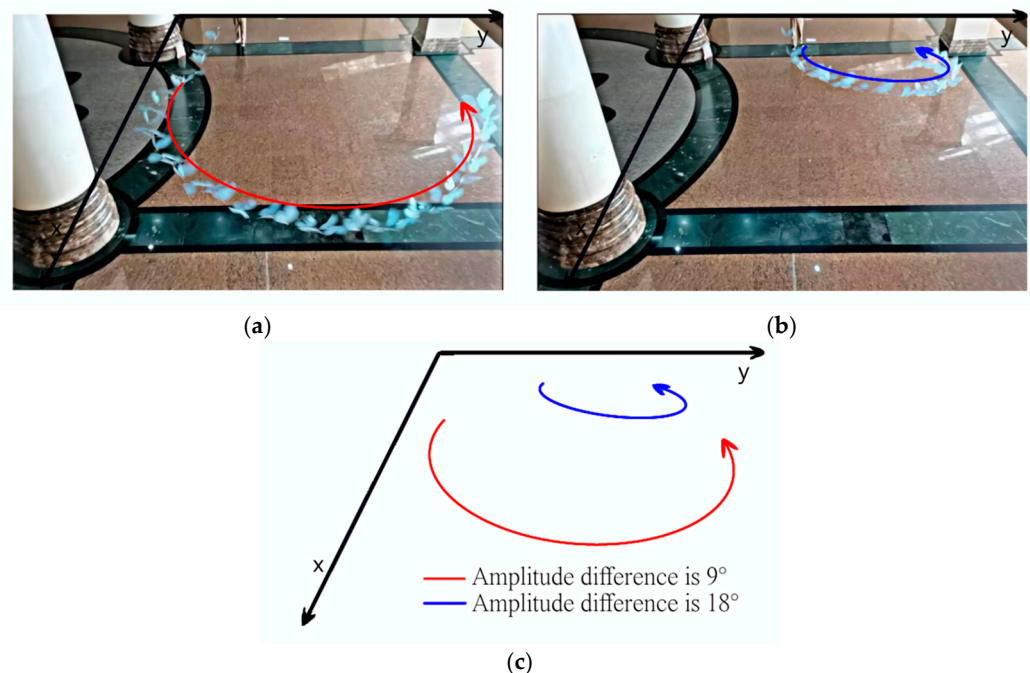


Figure 16. Results of Turning Test. (a) diagram with a 9° amplitude difference; (b) diagram with an 18° amplitude difference; (c) merged diagram of flight trajectories.

In both groups of experiments, the flapping amplitude of the left wing is greater than that of the right wing, and the flapping-wing aircraft turns left, indicating that the flapping-wing aircraft will turn to the side with a larger flapping amplitude.

When the amplitude difference is 9° , the turning radius is larger, and when the amplitude difference is 18° , the turning radius is smaller, indicating that the magnitude of the amplitude difference affects the turning performance of the flapping-wing aircraft, and the larger the amplitude difference, the tighter the turning radius.

The altitude of the flapping-wing aircraft decreases when turning, indicating that amplitude difference turning will affect the generation of lift to a certain extent. Before turning, the flapping-wing aircraft can be made to pitch backward and generate an upward trend, which can offset the downward trend caused by turning to a certain extent.

In summary, creating a difference in the flapping amplitude of the left and right wings can make the flapping-wing aircraft turn, and the flapping-wing aircraft will turn to the side with a larger flapping amplitude. The larger the amplitude difference, the tighter the turning radius. This is consistent with the results of the simulation calculation, indicating that the simulation results are basically accurate.

4.5. Flight Altitude Test: Impact of Change in Absolute Value of Mid-Position Angle on Flight Altitude of Flapping-Wing Aircraft

Three flight tests were carried out using the flight controller to input parameters, as shown in Table 12.

Table 12. Control parameter table of flight altitude test.

Control Parameters	(a)	(b)	(c)
Flapping frequency	4 Hz	4 Hz	4 Hz
Mid-position angle	5°	5° → 10°	5° → 0°
Flapping-wing aircraft	54°	54°	54°
Initial pitch angle	10°	10°	10°

The experimental results are shown in Figure 17.

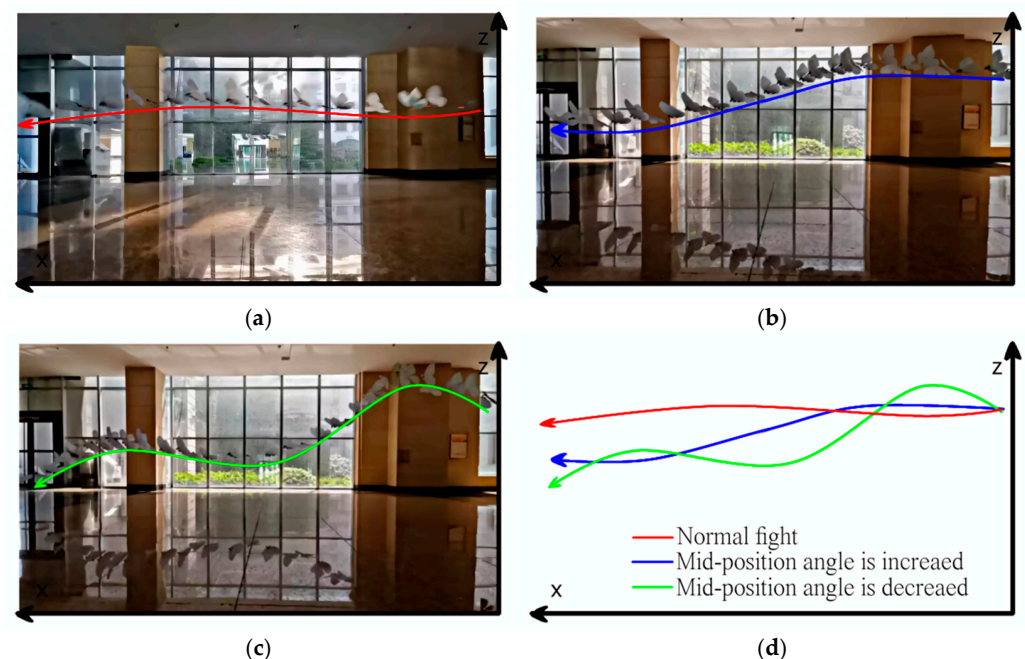


Figure 17. Results of Flight Altitude Test. (a) diagram when normal flight; (b) diagram when mid-position angle increases; (c) diagram when mid-position angle decreases; (d) merged diagram of flight trajectories.

When the absolute value of the mid-position angle increases, the flight trajectory of the flapping-wing aircraft slopes downward and then becomes horizontal again, indicating that increasing the absolute value of the mid-position angle can make the flapping-wing aircraft pitch forward and dive, and it has almost none impact on its flight capability. The position distribution of the flapping-wing aircraft is compact and close over time, indicating

that the generated propulsive force is weak. In general, increasing the absolute value of the mid-position angle can make the flapping-wing aircraft fly lower.

When the absolute value of the mid-position angle decreases, the flight trajectory of the flapping-wing aircraft fluctuates violently, indicating that decreasing the absolute value of the mid-position angle can make the flapping-wing aircraft pitch backward and climb, but it will significantly weaken its flight capability. The position distribution of the flapping-wing aircraft is compact when rising, indicating that the propulsive force generated during climbing is weak. In general, decreasing the absolute value of the mid-position angle can make the flapping-wing aircraft climb for a short time, but it will significantly reduce its flight capability, making it difficult to keep flying stably.

In summary, changing the absolute value of the mid-position angle during flight can control the flapping-wing aircraft's flight altitude by controlling the flapping-wing aircraft's pitching. Increasing the absolute value of the mid-position angle can make the flapping-wing aircraft pitch forward and dive, and it has almost no impact on its flight capability; decreasing the absolute value of the mid-position angle can make the flapping-wing aircraft pitch backward and climb, and the flight altitude can rise for a short time, but it will significantly reduce the flight capability.

There are some issues worthy of further exploration and discussion in the flight altitude test:

- (1) **Sudden Change of mid-position angle:** According to the experimental observation, a sudden increase in the absolute value of the mid-position angle will cause the flapping-wing aircraft to pitch forward sharply and then fall rapidly. Similarly, a sudden decrease in the absolute value of the mid-position angle will cause the flapping-wing aircraft to pitch backward sharply and even turn 180° in the vertical plane;
- (2) **Reduction of Propulsive Force Leads to a Reduction in Lift Generation:** In the experiment of decreasing the absolute value of the mid-position angle, the flapping-wing aircraft climbs and the propulsive force weakens, resulting in a decrease in the forward speed, and then its generated lift is not enough to overcome its own weight, then the flapping-wing aircraft dives. Try to use the calculation model established in Chapter 3 to analyze and explain this phenomenon: when the forward speed of the aircraft is too slow, the free stream velocity is only affected by the flapping speed, and the direction of the free stream is nearly perpendicular to the wing surface, that is, the angle of attack α of the flapping motion is approximately 90° , and the lift coefficient is about 0.1 using the empirical formula (4); the lift coefficient is extremely low, leading to a correspondingly small amount of lift. The theoretical analysis results are consistent with the experimental results, indicating that the theoretical analysis is basically correct. This is the main reason for the violent fluctuation of the flight trajectory of the flapping-wing aircraft;
- (3) **Impact of mid-position angle on Flight Capability:** In Experiment 3 of the lift test, a larger initial mid-position angle brought better flight capability, which is consistent with the results of simulation calculation analysis, while in this experiment, increasing the absolute value of the mid-position angle during flight eventually led to a decrease in flight altitude, which is consistent with the results of mathematical modeling analysis. There are two hypotheses about this. Firstly, when the absolute value of the mid-position angle is small, the direct impact of the mid-position angle on lift is the secondary impact, and the indirect impact on lift by affecting the angle of attack is the main impact; when the absolute value of the mid-position angle is slightly larger, the direct impact is the main impact. Secondly, in this experiment, the increase in the absolute value of the mid-position angle causes a change in the attitude of the flapping-wing aircraft, which was not reflected in Experiment 3. The mid-position

angle may affect the generation of lift by affecting the flight attitude. These two points need to be verified in future experiments.

5. Conclusions

This paper constructs a periodic function composed of two sine functions with different frequencies as the flapping function for the control of biomimetic flapping-wing aircraft. Through the creation of a rigid wing flapping lift computation model, the critical parameters within the flapping function that influence lift—the flapping amplitude, the flapping frequency, and the mid-position angles—have been isolated, and their effects on lift have been initially analyzed. To verify the accuracy and practicality of the modeling analysis results, two parts of work are carried out: simulation calculation and flight experiment. On the one hand, XFlow software is used for simulation calculation to verify and expand the results of modeling analysis; on the other hand, through biomimetic mechanism research, a biomimetic moth flapping-wing aircraft prototype for experiments is designed and manufactured, and a series of flight experiments such as lift test are carried out, and the flapping function is applied to the control of the aircraft. The comparison between the simulation and experimental results is shown in Table 13. Combining simulation and experiment, the impact of key parameters on the flight control of flapping-wing aircraft is as follows:

1. Flapping amplitude and flapping frequency are the key factors affecting the generation of lift of the flapping-wing aircraft. Increasing the flapping amplitude and flapping frequency can significantly improve the flight performance of the flapping-wing aircraft;
2. The difference in flapping amplitude between the left and right wings can make the flapping-wing aircraft turn, and the larger the amplitude difference, the tighter the turning radius;
3. The impact of the initial mid-position angle on the lift is the same as the results of the simulation calculation analysis. Increasing the mid-position angle can slightly improve the aerodynamic performance;
4. During flight, the change in the absolute value of the mid-position angle has the same impact on lift as the calculation results of the lift calculation model. At the same time, it will also affect the flight altitude of the flapping-wing aircraft. Increasing the absolute value of the mid-position angle can make the flapping-wing aircraft pitch forward and dive, and the flight altitude will decrease; decreasing the absolute value of the mid-position angle can make the flapping-wing aircraft pitch backward and climb, and the flight altitude can rise for a short time.

The research shows that by changing the key parameters and adjusting the flapping function of the two wings, the flight control of the flapping-wing aircraft can be realized. Furthermore, simultaneously adjusting multiple flapping function parameters can make the control of the aircraft more stable. For example, although decreasing the absolute value of the mid-position angle alone can make the flapping-wing aircraft climb for a short time during flight, the insufficient lift will quickly lead to stall and fall while simultaneously increasing the flapping amplitude and flapping frequency can make up for the lack of lift, so that the flight altitude can rise and keep flying stably. For another example, when turning the flapping-wing aircraft by using the amplitude difference alone, the flapping-wing aircraft tends to descend while simultaneously adjusting the absolute value of the mid-position angle to decrease and the flapping frequency to increase, which can offset this descending trend. In general, this study clarifies the key control parameters of flight control, which is helpful to optimize the existing control strategy of the flapping-wing

aircraft and improve the maneuverability and controllability of the aircraft; at the same time, the real-time controllable biomimetic flapping-wing prototype also provides reliable, practical support for the design and manufacturing of practical flapping-wing aircraft. This experimental prototype boasts a simple structure and low cost, rendering it highly suitable for use as a consumable across diverse scenarios. If further research can successfully reduce the wingspan, the prototype will become even more adept at handling tasks that demand stealth, such as reconnaissance missions.

Table 13. Comparison of simulation results and experimental results.

Test	Parameters	Simulation Result	Experimental Result	Comparison
Lift Test Experiment 1	Flapping amplitude	Increasing the flapping amplitude can improve the aerodynamic performance of the flapping motion	Increasing the flapping amplitude can enable the aircraft to obtain better flight performance	Consistent
Lift Test Experiment 2	Flapping frequency	Increasing the flapping frequency can improve the aerodynamic performance of the flapping motion	Increasing the flapping frequency can enable the aircraft to obtain better flight performance	Consistent
Lift Test Experiment 3	Mid-position angle	Increasing the mid-position angle can slightly improve the aerodynamic performance	Increasing the mid-position angle can enable the aircraft to obtain better flight performance	Consistent
Turning Test	Flapping amplitude difference	Increasing the flapping amplitude of the left wing and decreasing the flapping amplitude of the right wing can achieve left turn of the aircraft	The flapping-wing aircraft will turn to the side with a larger flapping amplitude. The larger the amplitude difference, the tighter the turning radius	Consistent
Flight Altitude Test	Absolute value of the mid-position angle	N/A	Increasing the absolute value of the mid-position angle can make the flapping-wing aircraft pitch forward and dive decreasing the absolute value of the mid-position angle can make the flapping-wing aircraft pitch backward and climb	N/A

It should be noted that due to the simplification of the calculation model and the neglect of wing deformation, the impact of the mid-position angle on the flight effect of the flapping-wing aircraft has not been clarified. Subsequent research will continue to focus on the study of this key parameter of mid-position angle, focusing on exploring the impact of mid-position angle on the angle of attack under the premise of considering wing deformation, constructing a more detailed calculation model, designing more reasonable flight experiments, and improving the flight control strategy of the flapping-wing aircraft in complex situations.

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References

1. Tan, J.; Wang, Y.; Wang, Y. The Research Progress of the Rotary-Wing Flight Robot. *Control Theory Appl.* **2015**, *32*, 1278–1286.
2. Singh, S.; Zuber, M.; Hamidon, M.N.; Mazlan, N.; Basri, A.A.; Ahmad, K.A. Classification of actuation mechanism designs with structural block diagrams for flapping-wing drones: A comprehensive review. *Prog. Aerosp. Sci.* **2022**, *132*, 100833. [CrossRef]
3. Ryan, M.; Su, H.-J. Classification of flapping wing mechanisms for micro air vehicles. In Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference: 2012, Chicago, IL, USA, 12–15 August 2012; American Society of Mechanical Engineers: New York, NY, USA, 2012; pp. 105–115.
4. Nguyen, Q.V.; Chan, W.L.; Debiassi, M. Hybrid Design and Performance Tests of a Hovering Insect-inspired Flapping-wing Micro Aerial Vehicle. *J. Bionic Eng.* **2016**, *13*, 235–248. [CrossRef]
5. Ellington, C.P. The novel aerodynamics of insect flight: Applications to micro-air vehicles. *J. Exp. Biol.* **1999**, *202*, 3439–3448. [CrossRef] [PubMed]
6. eMotionButterflies. Available online: https://www.festo.com.cn/cn/en/e/about-festo/research-and-development/bionic-learning-network/highlights-from-2015-to-2017/emotionbutterflies-id_33454/ (accessed on 16 August 2024).
7. BionicOpter. Available online: https://www.festo.com.cn/cn/en/e/about-festo/research-and-development/bionic-learning-network/highlights-from-2013-to-2014/bionicopter-id_33493/ (accessed on 16 August 2024).
8. Wood, R.J. Liftoff of a 60mg flapping-wing MAV. In Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems: 2007, San Diego, CA, USA, 29 October–2 November 2007; IEEE: New York, NY, USA, 2007; pp. 1889–1894.
9. BionicBee. Available online: https://www.festo.com.cn/cn/en/e/about-festo/research-and-development/bionic-learning-network/bionicbee-id_1659889/ (accessed on 16 August 2024).
10. Xu, H.; Wang, Y.; Pan, E.; Xu, W.; Xue, D. Autonomous Formation Flight Control of Large-Sized Flapping-Wing Flying Robots Based on Leader–Follower Strategy. *J. Bionic Eng.* **2023**, *20*, 2542–2558. [CrossRef]
11. Chang, M.; Xu, Z.; Chen, Z.; Li, L.; Meng, X. Aerodynamic Performance of Three Flapping Wings with Unequal Spacing in Tandem Formation. *J. Bionic Eng.* **2024**, *21*, 1662–1676. [CrossRef]
12. Leng, Y.; Zhang, W.; Zhou, S.; Chen, X.; Ge, W. Design and Analysis of Bionic Butterfly Aircraft. *Mech. Des. Res.* **2019**, *35*, 32–35+42.
13. He, W.; Liu, S.; Huang, H.; Fu, Q.; Sun, C. System design and experiment of an independently driven bird-like flapping-wing robot. *Control Theory Appl.* **2022**, *39*, 12–22.
14. Tudose, L.; Budaciu, C. Design and implementation of a butterfly robot system. In Proceedings of the 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA): 2019, Zaragoza, Spain, 10–13 September 2019; IEEE: New York, NY, USA, 2019; pp. 1665–1668.
15. Fujikawa, T.; Hirakawa, K.; Okuma, S.; Udagawa, T.; Nakano, S.; Kikuchi, K. Development of a small flapping robot: Motion analysis during takeoff by numerical simulation and experiment. *Mech. Syst. Signal Process.* **2008**, *22*, 1304–1315. [CrossRef]
16. Fujikawa, T.; Shindo, M.; Kikuchi, K. Motion analysis of pitch rotation mechanism for posture control of butterfly-style flapping robot. *Am. Trans. Eng. Appl. Sci.* **2014**, *3*, 251–263.
17. Sato, Y.; Yamashita, T.; Kikuchi, K. Development of a lead-lag mechanism using simple flexible links for a small butterfly-style flapping robot. In Proceedings of the 2010 World Automation Congress: 2010, Kobe, Japan, 19–23 September 2010; IEEE: New York, NY, USA, 2010; pp. 1–6.
18. Richards, O.W.; Davies, R.G. *Imms' General Textbook of Entomology*; Springer: Berlin/Heidelberg, Germany, 1957.
19. Ahmad, H.; Markina, A.; Porotnikov, M.; Ahmad, F. A review of carbon fiber materials in automotive industry. In *IOP Conference Series: Materials Science and Engineering*: 2020; IOP Publishing: Bristol, UK, 2020; Volume 032011.
20. Béthoux, O.; Nel, A. Venation pattern of Orthoptera. *J. Orthoptera Res.* **2001**, *10*, 195–198. [CrossRef]
21. Yan, Y.; Song, F.; Xu, N.; Zhu, H.; Xing, H.; Zhang, S.; Sun, J. Study on the vibration reduction characteristics of FWMAV flexible bionic wings mimicking the hindwings of *Trypoxylus dichotomus*. *J. Bionic Eng.* **2023**, *20*, 2179–2193. [CrossRef]
22. Weis-Fogh, T. Quick estimates of flight fitness in hovering animals, including novel mechanisms for lift production. *J. Exp. Biol.* **1973**, *59*, 169–230. [CrossRef]
23. Ellington, C.P.; Van Den Berg, C.; Willmott, A.P.; Thomas, A.L. Leading-edge vortices in insect flight. *Nature* **1996**, *384*, 626–630. [CrossRef]
24. Dickinson, M.H.; Lehmann, F.-O.; Sane, S.P. Wing rotation and the aerodynamic basis of insect flight. *Science* **1999**, *284*, 1954–1960. [CrossRef]

25. Pan, Y.; Guo, S.; Huang, X. Research progress on bio-inspired flapping-wing rotor micro aerial vehicle development. *J. Bionic Eng.* **2024**, *21*, 1621–1643. [[CrossRef](#)]
26. Schenato, L.; Deng, X.; Wu, W.C.; Sastry, S. Virtual insect flight simulator (VIFS): A software testbed for insect flight. In Proceedings of the 2001 ICRA IEEE International Conference on Robotics and Automation (Cat No 01CH37164): 2001, Seoul, Republic of Korea, 21–26 May 2001; IEEE: New York, NY, USA, 2001; pp. 3885–3892.
27. Sane, S.P.; Dickinson, M.H. The control of flight force by a flapping wing: Lift and drag production. *J. Exp. Biol.* **2001**, *204*, 2607–2626. [[CrossRef](#)] [[PubMed](#)]
28. Shimura, K.; Aono, H.; Kang, C.-k. An Experimental Study on Response and Control of a Flapping-Wing Aerial Robot Under Wind Gusts. *J. Bionic Eng.* **2024**, *21*, 209–223. [[CrossRef](#)]

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