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Lightweight Design and Study of Mechanical Bionic Butterfly Aircraft Based on Finite Element Analysis

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ABSTRACT: *With the rapid development of science and technology, bionics has shown great potential and application value in many fields. Through the deep observation and understanding of real butterflies, the innovative idea of the design of mechanical bionic butterfly has been proposed, and the lightweight design and research of mechanical bionic butterfly have been discussed in detail by combining the advanced material science and structural optimization technology in the paper. Thus, The research results make the mechanical bionic butterfly achieve more efficient and more natural flight performance, and provide a solid theoretical basis and practical guidance for the lightweight design of mechanical bionic butterfly.*
Keywords: *Bionic butterfly, Structure optimization, Lightweight, Finite element analysis*

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I. INTRODUCTION

With the rapid development of science and technology, as an interdisciplinary research field, bionics is gradually showing its great application potential and value in mechanical engineering, material science, biology and other fields. By imitating the structure, function and behavior principles of natural organisms, bionics provides novel ideas and solutions for the design and optimization of artificial systems. Among them, mechanical bionic butterfly, as an important direction of bionics research, is to achieve more efficient and natural flight performance by imitating the flight principle and structural characteristics of real butterflies. Yixin Zhang et al. studied the flight mechanism of butterflies, and carried out a number of design and testing work of bionic aircraft based on this.[1] Jiawei Jiang et al. have studied a comprehensive and rigorous analysis of the flight mechanism of butterflies with the help of advanced instruments and techniques. Through high-speed photography, wind tunnel test and computer simulation, we have successfully revealed the complex structure, flapping frequency, Angle and trajectory of butterfly wings on their flight performance.[2]

The lightweight design of the mechanical bionic butterfly is the key technology to realize its efficient flight. With their light body shape and excellent flying ability, real butterflies show amazing flight efficiency in nature. Therefore, on the basis of the real butterfly flight mechanism research, combined with advanced material science and structure optimization technology, an innovative mechanical bionic butterfly lightweight design scheme has been put forward, the selection of lightweight materials and structure design method has been elaborated. A bionic butterfly with lightweight structure that meets both the bionic principle and practical application needs is designed. And through numerical simulation and butterfly test, verify the feasibility and effectiveness of the design scheme. It provides the theoretical basis and practical guidance for the design of mechanical bionic butterfly.

II. Theoretical Analysis of Butterfly Structure and Flight Mechanism

2.1 The structure of the butterfly

The body structure of the butterfly is mainly composed of three parts: head, chest and abdomen. The head is the concentration of sensory organs of butterflies, with a pair of large and complex compound eyes that can sense the strength and direction of light. The chest is the main motor organ of the butterfly, with three pairs of feet and two pairs of wings. Wings are the most striking feature of butterflies. They not only have bright colors and unique patterns, but also have the key function of flight. The abdomen is responsible for life activities such as digestion, excretion and reproduction. [3-4]

The wing structure of the butterfly is very special, consisting of thin-shaped transparent wings and pulse wings. This structure is light and strong, which helps to reduce the resistance during flight. The surface of the wings is covered with tiny scales that reflect the sunlight and make the butterflies even more dazzling when flying. At the same time, the scales also protect the wings from damage.[5]

2.2 Flying mechanism of butterflies

The flight mechanism of butterflies involves aerodynamic principles. When a butterfly flapping its wings, it creates air flow. According to Bernoulli's law, the pressure decreases. Butterflies use this principle to form areas of low pressure above the wing and high pressure below the wing. This pressure difference creates lift, supports the butterfly flight. In addition, butterflies are able to flexibly adjust the angle and frequency of their wings to meet different flight needs.[6]For example, when rises, butterflies flap their wings to increase lift; when falls, they close their wings to reduce resistance. In addition to wing vibration and air pressure differences, butterfly flight is influenced by environmental factors. Butterflies will choose their flight routes based on the wind direction and wind speed to reduce flight resistance. They also use hot air to raise their height, saving their energy. This flight strategy allows butterflies to shuttle flexibly through complex environments, showing their unique flight charm.[7]

III. Lightweight Design of Bionic Butterflies

3.1 Selection of materials

In order to realize the lightweight design of mechanical bionic butterflies, we investigated various lightweight materials and analyzed their properties. The performance parameters of each part of the material were shown in Table 1.

Table 1 Performance parameters of the materials

Material	Modulus of elasticity /MPa	Poisson ratio	Density g/mm^3	Yield strength /MPa
T300	2.300e11	0.330	8.00e-3	3.880e3
PLA	4.000e3	0.400	1.280e-3	5.000e1
Steel （AISI304）	1.950e5	0.290	8.000e-3	2.150e2
PET	7.850e1	0.290	1.380e-3	2.000e2

(1) Wing skeleton: In order to meet the main body support, and has a high strength, lightweight architecture. The skeleton of the wings is shown in Figure 1, using carbon fiber composite as the main scaffold of the butterfly wings, and using 0.8mm, 0.5mm carbon fiber rod in diameter for different wing secondary and main rods.[8]

(2) Wing ailerons: The material selection and structural design of wing ailerons are very important in the lightweight design of mechanical bionic butterflies, which directly affect the flight stability, durability and overall lightweight effect of bionic butterflies. The wing aileron structure is shown in Figure Figure 2. To meet the requirements, 304 stainless steel with 0.3mm thickness is used in this paper. [9] Composite structure with the PVC material and cleverly incorporated a thin wire to enhance its properties.

(3) Flexible wing of butterfly: the flexible wing part adopts 0.0125mm thick PET (polyester polyester) film, the film has the characteristics of high temperature resistance and transparency, so that it can ensure its mild under the condition of guaranteed strength.

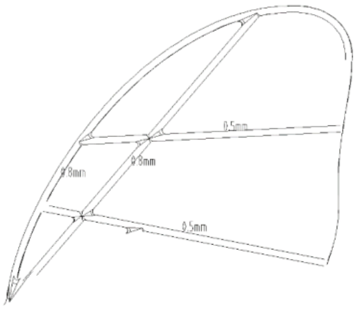


Fig. 1 Wing skeleton

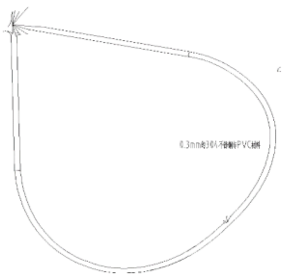


Fig. 2 Aileron structure of wings

3.2 Structure optimization and design

3.2.1Optimization of butterfly wing movement mechanism

Under specific numerical simulation conditions, it is found that increasing the wing frequency will significantly increase the average lift, but the effect on the average thrust is not obvious; increasing the wing frequency does increase the average aerodynamic coefficient in each cycle.[10]

Therefore, in order to improve the flight frequency of mechanical bionic butterflies, the control of the elevation Angle is studied, and the crank lever mechanism is used to control the movement of the butterfly. The principle of the mechanism is shown in Figure 3.

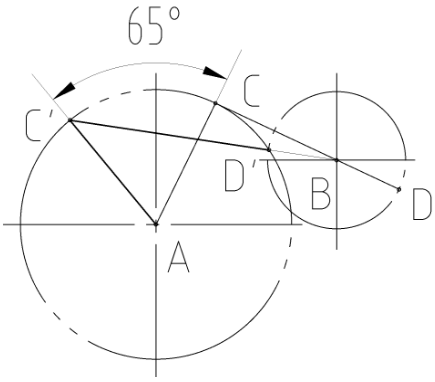


Fig. 3 Schematic diagram of butterfly wing movement

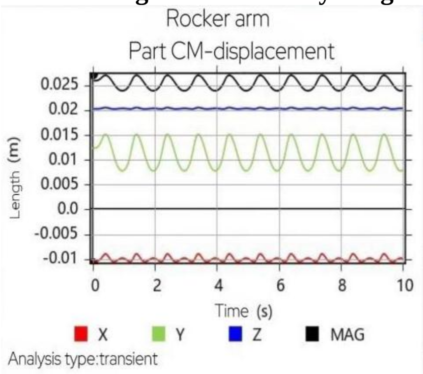


Fig. 4 Apical displacement diagram of the rocker arm

The motor is installed at point B, and the motor drives the slot wheel to move around around point B. The D end of the rocker arm CD is installed on the slot wheel. When the slot wheel rotates, the rocker arm CD is driven to swing, thus driving the wings to flutter. The CD and C'D′ in Figure 3 are the start and end positions of the rocker arm, respectively, with a maximum swing angle of 65°. The instantaneous displacement of the rocker arm is shown in Figure 4.

3.2.2 Estimation and checking of butterfly wing volume and quality

In order to ensure the feasibility of the mechanical operation, the overall structure is analyzed.

(1) Initially model the butterfly model and estimate its volume and quality. Butterfly modeling is shown in Figure 5.

(2) The force area of the wing was measured, adjusted, and then optimized to calculate that the area of a single wing is 30084.48mm² and the total area is 60168.96mm².

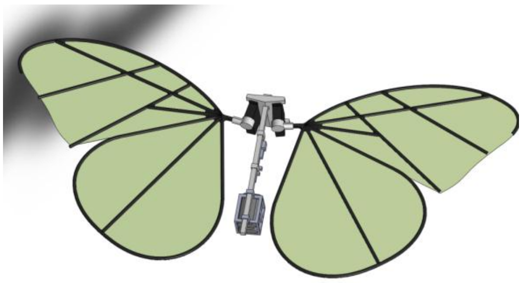


Fig. 5 3 D modeling of the butterflies

(3) Theoretical load of the rocker arm

The theoretical load of the rocker arm is shown in Figure 6, The individual rocker arm was theoretically subjected to an overall load of 5.3g, 0.0125mm PET film is 0.157g (replaced with equal mass ball in Figure6), The exposed air pressure was 1.7617e-06 MPa, It was analyzed by using the Altair inspire software, The maximum safety factor obtained is 3.767e + 06, The maximum compressive stress is 8.361e-02MP a, Mises maximum equal effect force 8.535e-02MP a, Less than the maximum stress of the selected material, Meet the basic condition requirements.

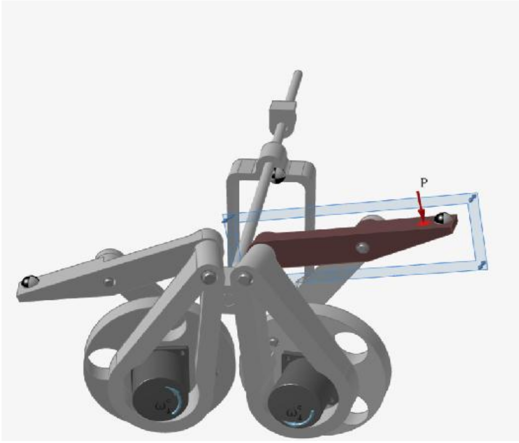


Fig. 6 Theoretical load of the rocker arm

(4) Check the flight physical parameters

Various flight physical parameters are correlated by dimensional analysis. According to the mathematical statistical approximation, the aerodynamic important parameters of flapping wing flight, which are related to mass m, and both show the mathematical relationship of power exponential function. If the total mass of bionic butterfly is set to 10.6g, the empirical formula. [11-12] The following calculations can be obtained:

1) The bionic butterfly has a full wingspan of b

$$b = 1.24 \times m^{0.37} \quad (1)$$

Plug in the numbers. Have to

$$b = 1.24 \times m^{0.37} = 1.24 \times (10.6 \times e - 03)^{0.37} = 0.23\ \text{(m)}$$

0.23m is less than 0.281m.

2) Wing surface area of the bionic butterfly is S

$$S = 0.16 \times m^{0.67} \quad (2)$$

Plug in the numbers. Have to

$$S = 0.16 \times m^{0.67} = 0.16 \times (10.6 \times e - 03)^{0.67} = 7604.5743\ \text{(mm}^2\text{)}$$

Wing area S is the core parameter that determines the aerodynamic characteristics of the aircraft, which is positively correlated with the air force of the wing 7604.5743mm² is much less than the actual wing area 60168.96mm²

3) Bionic butterfly chord ratio AR

$$AR = 9.37 \times m^{0.07} \quad (3)$$

Plug in the numbers. Have to

$AR = 9.37 \times (10.6 \times e - 03)^{0.07} = 6.793916$

The AR value shows a positive correlation between the lift-resistance ratio of the bionic butterfly. Specifically, when the AR value is large, it helps to improve the energy efficiency of the bionic butterfly and significantly enhance its flying ability; on the other hand, if the AR value is small, the bionic butterfly will show excellent mobility, however, in this case will be accompanied by large energy loss, thus limiting its ability to fly for a long time. The AR value of the current design is 7.44915, which exceeds the AR value standard of the theoretical bionic butterfly chord ratio.

Through calculation, the size of the bionic butterfly meets the theoretical requirements and is able to fly.

3.3 Configuration of the power system

In order to realize the efficient flight of the mechanical bionic butterfly, to meet the data of this mechanical bionic butterfly. The Altair inspire software was used to obtain the torque and frequency of the required motor. The system uses a combination of micro-motors and a high energy density battery to provide continuous and stable power support. We also optimized the layout and weight distribution of the power system to ensure the balance and stability of the mechanical bionic butterfly during flight. The six mm micro-610 hollow cup deceleration motor used in the paper; the instantaneous torque of the motor is shown in Figure 7. The specific parameters are as follows:

Data: gearbox deceleration ratio is 1:700;

Voltage: 3V; current: 45 mA (blocking rotating current: 200 mA);

Motor speed: 32000 rpm; outgoing shaft speed: 40 rpm;

Torque: 200g \ cm (plugging torque: 300g \ cm);

Voltage: 1.5V current: 25 mA (blocking rotation current 100 mA);
Motor speed: 17,000 rpm, output shaft speed: 20rpm;
Torque: 100g \ cm (blocking torque 150g \ cm).

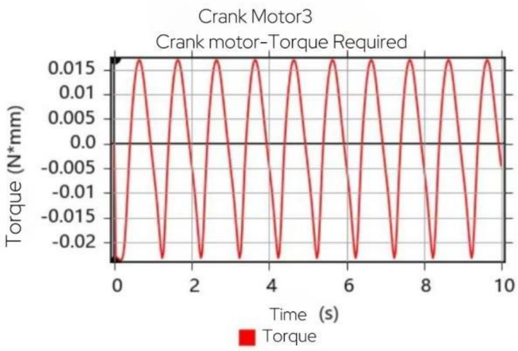
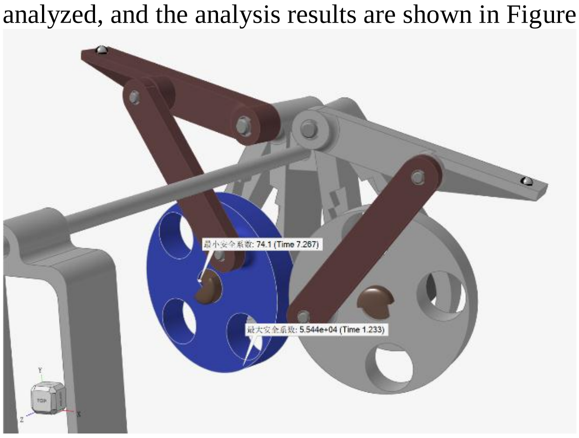


Fig. 7 Instantaneous torque of the motor

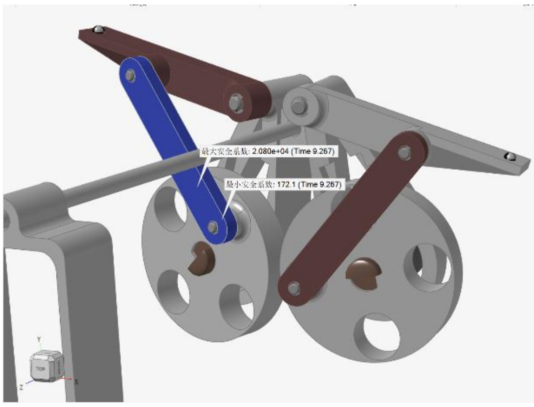
After examination, the motor meets the design required torque and frequency.

3.4 Finite element analysis of other mechanism models

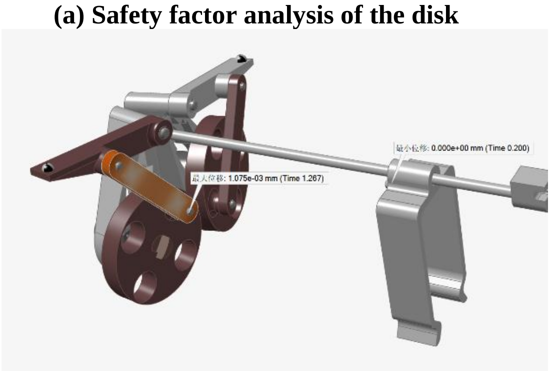
The finite element analysis of the mechanism model except the rocking arm parts was conducted by Altair inspire software, and the maximum safety factor and minimum safety factor, maximum displacement, minimum displacement, maximum Mises equivalent coefficient and minimum effect force coefficient were analyzed, and the analysis results are shown in Figure 8.



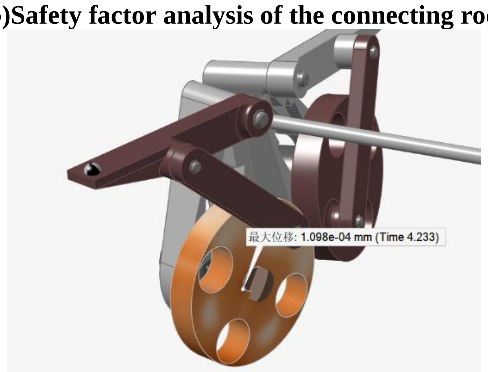
(a) Safety factor analysis of the disk



(b)Safety factor analysis of the connecting rod



(c) Deformation analysis of the connecting rod



(d) Deformation analysis of the disk

Fig. 8 Results of the FEM model analysis

The analysis shows that the minimum safety factor, the maximum displacement and the maximum rice equivalent factor of the connecting rod and the disk can meet the strength required by the mechanical butterfly in flight.

IV. Flight Test and Result Analysis

In order to verify the feasibility of the lightweight design scheme, we conducted the physical production of the mechanical bionic butterfly, and the final product is shown in Figure 9. The physical weight is 10.6g, as shown in Figure 10. After takeoff, the flapping frequency of the butterfly wings is 0.067Hz, and the actual area of the wing is 61575.21mm2, Flight distance is 30m.

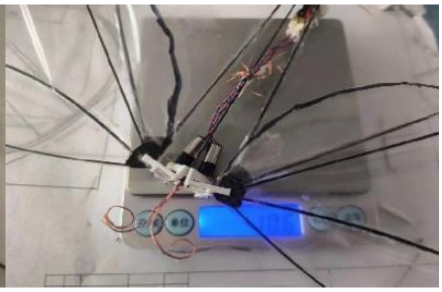


Fig. 9 Physical model **Fig. 10 Physical weight**

V. Conclusion

Based on the theoretical analysis of the structure and flight mechanism of butterflies, the paper simulates the efficient flight performance of real butterflies, and proposes the lightweight design scheme of bionic butterflies. Using advanced materials such as carbon fiber composite material and combined with structural optimization technology, the lightweight design of the main bracket of mechanical bionic butterfly is realized. The flight performance of the bionic butterfly is further optimized by adjusting the flight frequency and elevation angle by the crank lever mechanism. Mathematical statistics are used to determine the flight physical parameters of bionic butterflies, such as full wingspan, wing plane area and aspect ratio. The bionic butterfly is equipped with advanced power systems such as micro-motors and high-energy-density batteries. A finite element analysis of the mechanism model except for the rocker parts was performed using Altair inspire software. The feasibility of the lightweight design scheme is verified through the test flight test. The lightweight design and research of the mechanical bionic butterfly provide new ideas for the development of the micro-aircraft field, and provide strong technical support for the development of the mechanical bionics field and the practical application of related fields.

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