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Optimization of an Insect-like Flapping Wing Mechanism

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Abstract: *One of the challenges in Flapping-Wing Micro Air Vehicle (FWMAV) is to make the wing tip always trace a flat figure-eight whilst ensuring the quality of the robot remains as light as possible. This paper optimized an existing mechanism so that the motion of the wingtip matched the actual flight state of the insect with a single-degree-of-freedom drive. The kinematic model of the FWMAV mechanism was constructed. Based on non-linear programming, the length ratio of the key part of the mechanism was obtained, meanwhile, theoretical calculations were confirmed by ADAMS simulations. The optimized Insect-like Flapping-Wing Mechanism had a satisfied performance with an upward flapping of 60°, a downward angle of 24.99° and a swing angle of 10.71°, whose wingtip exhibited an "8" shape.*

Keywords: *Flapping-Wing mechanism; Kinematic analysis; Non-linear programming*

1. Introduction

Insect- and bird-size drones--micro air vehicles (MAVs) are used to perform missions such as surveillance, planetary exploration, search-and-rescue and so on in a hostile environment [1-2]. Among MAVs, Flapping-Wing Micro Air Vehicles (FWMAVs) have advantages of higher maneuverability, lower noise, and better concealment compared with fixed-wing aircrafts and rotorcrafts [3], which currently make them an active research area.

The flight state of insects in nature can guide the design of a flapping wing aircraft. As shown in Figure 1, insect flapping-wing movements include flapping, twist, and swing, which make the wing tip of insects always traces a flat figure-eight around a certain plane [4]. This type of movement has also been shown to be effective in increasing mean lift [5].

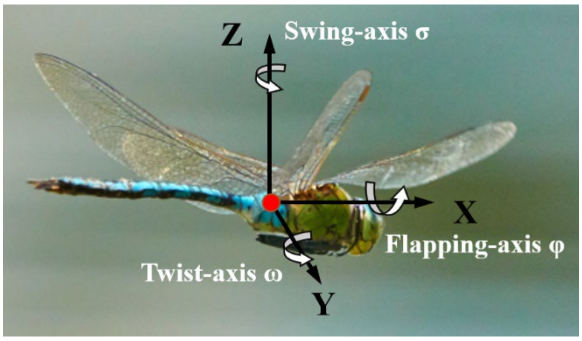


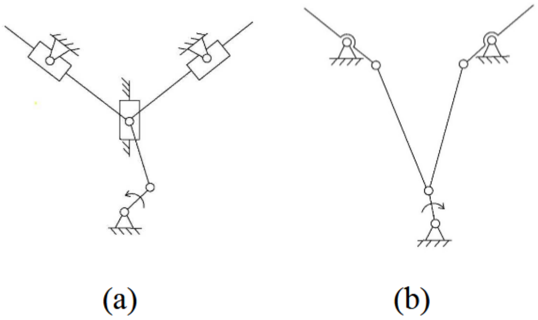
Figure 1. A dragonfly during flight

The flapping-wing mechanisms can be divided into single-degree-of-freedom mechanisms (1DOF) and multiple degrees of freedom ones (DOFs). The flapping mechanisms with 1DOF are relatively simple, which are often based on a crank rocker mechanism [6-7]. However, it's hard to mimic figure-eight flapping motions with 1DOF. Another type of mechanisms (DOFs) is often based on multiple linkages or several servos to mimic flapping-twist-swing motion [8-9], but design and control complexity are increased. Therefore, it is necessary to design a mechanism that can achieve a figure-eight trajectory for the wingtips.

In this paper, based on the mechanism by Chen, kinematic modelling and optimal design of the mechanical structure were suggested. Ideal bionic performance of a flapping wing was achieved with a motor driven at certain speed.

2. Flapping-Wing Mechanism Design

To convert the rotational motion of the motor into a flapping motion of wings, crank-slider mechanism and single-crank-and-double-rocker mechanism are widely used [10] [see Fig. 2]. For crank rocker mechanism, the asymmetry of the mechanism leads to asynchronous motion of the left and right wings, resulting in instability during flight. For crank slider mechanism, transmission efficiency of the mechanism is significantly reduced. Moreover, neither mechanism can achieve a figure-eight movement of the wingtip.



(a) crank-slider mechanism; (b) single-crank-and-double-rocker mechanism

Figure 2. Commonly used flapping mechanism.

The mechanism proposed by Chen in Figure 3 is a solution to the above problem [11]. It can be seen as combining a crank slider mechanism and a crank rocker mechanism, both of which share a common crank. When the motor drives the crank, the slider reciprocates on the rocker, presenting a flat figure-eight. In order to reflect the trajectory on the wing, a magnification device was designed. A spherical joint bearing is used at the pivot point of the Inner Wing Rod and the frame. It enables the outer wing rod to move to achieve a bigger 'figure-eight'.

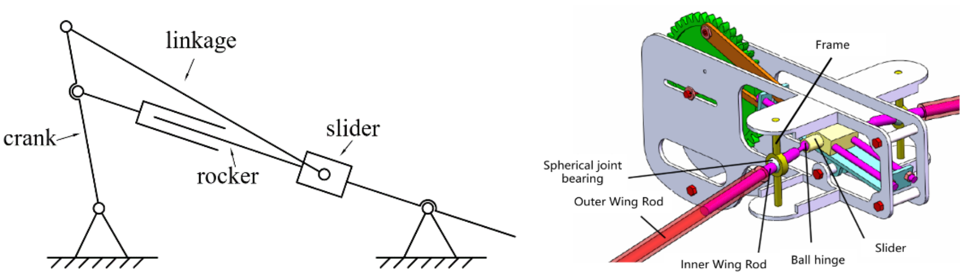


Figure 3. A mechanism for achieving an "8" shaped wing tip trajectory

3. Kinematic analysis of flapping mechanisms

Since the trajectory of the two wings are symmetrical about the insect body axis, only the left-hand mechanism was analyzed kinematically in this paper. Establish a Rectangular Coordinate System with point D as the origin as shown in Figure 4. The lengths of EA, AB, BC, ED and CD are L_1, L_2, L_3, L_4 and x respectively. θ is the rotation angle of crank AB, α is $\angle xDA$ and β is the angle between BC and AC. Define the X-Y coordinate plane as Flapping-Wing plane.

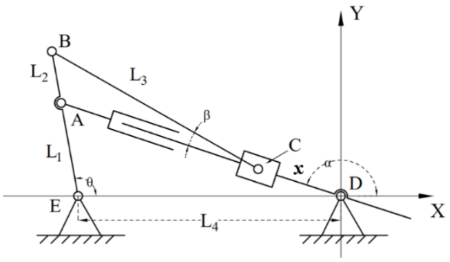


Figure 4. Flapping mechanism

The coordinates of the points are

$$A\left(-L_4+L_1\cos\theta, L_1\sin\theta\right),\ B\left(-L_4+L\cos\theta, L\sin\theta\right),\ C(x\cos\alpha, x\sin\alpha), D(0,0)$$

Since $BC = L_3$,

$$(x_B - x_C)^2 + (y_B - y_C)^2 = L_3^2 \tag{1}$$

$$\begin{aligned} &x^2 + (-2L\cos\theta\cos\alpha + 2L_4\cos\alpha - 2L\sin\theta\sin\alpha)x \\ &+(L_4{}^2 - 2L_4L\cos\theta - L_3^2 + L^2) = 0 \end{aligned} \tag{2}$$

Solving the equation,

$$x = \frac{-B \pm \sqrt{B^2 - 4C}}{2} \tag{3}$$

where

$$\begin{cases} \alpha = \arctan\dfrac{L_1\sin\theta}{L_4 - L_1\cos\theta} \\ L = L_1 + L_2 \\ B = -2L\cos\theta\cos\alpha + 2L_4\cos\alpha - 2L\sin\theta\sin\alpha \\ C = L_4{}^2 - 2L_4L\cos\theta - L_3^2 + L^2 \end{cases} \tag{4}$$

With x and α, the trajectory of point C can be found, which has a definite ‘figure-eight’ movement.

4. Mechanism optimization

In order to make the wing tip mimic the movement of an insect better, the mechanism needs to be optimized.

4.1 Selection of optimization variables

The trajectory of point C on slider decides the trajectory of the wing tip. According to Equation 3 and Equation 4, the shape of the trajectory of point C is related to L_1, L_2, L_3, L_4. The trajectory of the wing tip is also related to the distance L_5 of the Flapping-Wing plane from the spherical joint bearing when considering a magnifying device. To simplify the calculation, the value of L_5 is set to 1. Optimization variables can be defined as

$$X = [L_1, L_2, L_3, L_4] \tag{5}$$

4.2 Nonlinear Constraints

1) In order for the trajectory of point C to be a definite ‘figure-eight’ movement, Equation 3 must have one solution at least:

$$B^2 - 4C \geq 0 \tag{6}$$

2) As the mechanism is combination of a crank slider mechanism and a crank rocker mechanism, the lengths of the rods need to meet the specific condition [12]:

$$\begin{cases} L_1 < L_4 \\ L_1 + L_2 < L_3 \end{cases} \tag{7}$$

3) During the movement, the greater the transmission angle is, the more favorable it is for the force

transmission of the mechanism [12]. In general, the transmission angle needs to be no less than 40°. Therefore, the transmission angle between the BC and the AD rod should satisfy

$$\gamma_1 = \left|90 - \arccos(\overrightarrow{BC}, \overrightarrow{AD})\right| \geq 40^{\circ} \tag{8}$$

4.3 Target functions

In this paper, the wing motion of an insect during hovering was used to establish the target functions. Mou showed that the upward and downward flapping angles φ of the insect were approximately 60° and 25°. The swing angle was about 10°, approximately considered symmetrical [13]. Thus, the target function is

$$\begin{aligned} f_1(\mathbf{X}) &= \left|\varphi_{up} - 60\right| \\ f_2(\mathbf{X}) &= \left|\varphi_{down} - 25\right| \\ f_3(\mathbf{X}) &= \left|\delta_{\max} - 10\right| \end{aligned} \tag{9}$$

In order to integrate the effects of flapping and swing angle, a multi-objective optimization model needs to be established. Assign weights w_1, w_2, w_3 to each of the three objective functions in Equation 9, which represents the importance of flapping and swing angle respectively. After linear weighting, the evaluation function can be expressed as

$$f(\mathbf{X}) = \left[w_1, w_2, w_3\right] \bullet \begin{bmatrix} f_1(\mathbf{X}) \\ f_2(\mathbf{X}) \\ f_3(\mathbf{X}) \end{bmatrix} \tag{10}$$

$$w_1 + w_2 + w_3 = 1$$

In the paper, w_1, w_2, w_3 are assigned 0.4, 0.4, 0.2, according to the degree of contribution of the flapping and swing angle to the mean lift [5].

5. Optimization results

After specifying the constraints, the optimization was carried out using the non-linear programming function *fmincon* in MATLAB [14].

Considering the size requirements of FWMAVs and the difficulty of manufacture, initial values and ranges of optimization parameters can be expressed as

Table 1. Initial value and range of linkage parameters

	L1	L2	L3	L4
Initial value	1	1	3	2
Minimum value	0.5	0.5	0.5	0.5
Maximum value	10	10	10	10

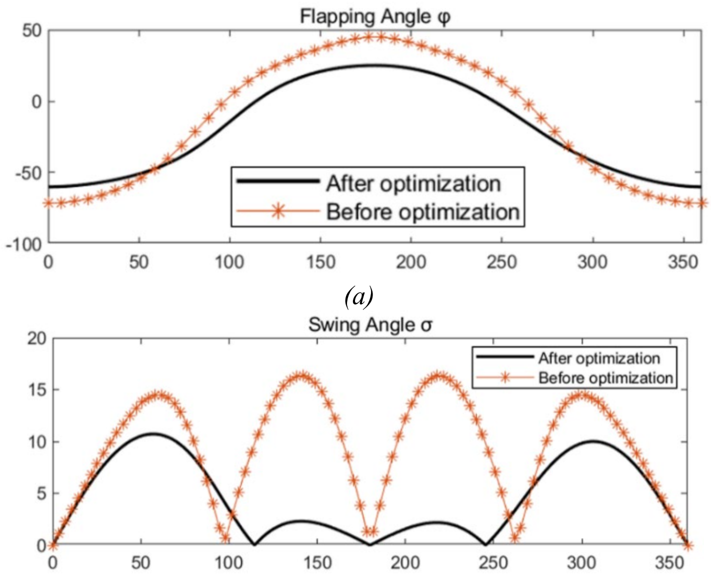
Optimization by *fmincon* results in

$$X = [0.5857\ , 0.5135,\ 2.9189,\ 2.2860]$$

Apply a torque to the prime mover and turn it 360° (one cycle) to observe output angles. Table 2 and Figure 5 show the flapping, swing, and transmission angles after optimization.

Table 2. Range of output angles

	Flapping Angle φ	Swing Angle σ	Transmission Angle γ
Maximum value/°	-60.00	10.71	90.00
Minimum value/°	24.99	0	79.87



(a)

(b)

Figure 5. Comparison of output angles before and after optimization

As can be seen from Table 2 and Figure 5, within a flapping cycle, the flapping angle varies from -60° to 24.99°, i.e., the upward and downward angles are 60° and 24.99°. The swing angle varies from 0 to 10.71°. The transmission angle varies from 79.87° to 90°. Each of the angles satisfies the constraint.

6. Mechanism simulation verification

In order to verify the optimized motion characteristics of the Flapping-Wing mechanism in this paper, simulations were carried out using Adams. The lengths of components were set according to the theoretical calculation results, suitable connection subs were installed and then a rigid body model was established [see Figure 6].

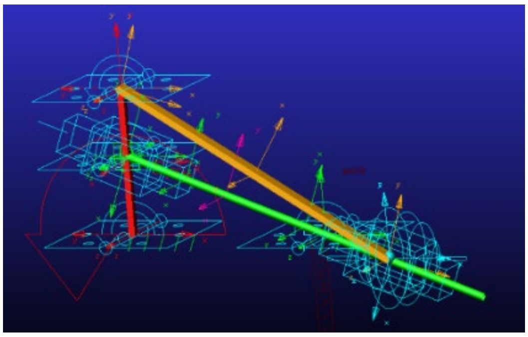
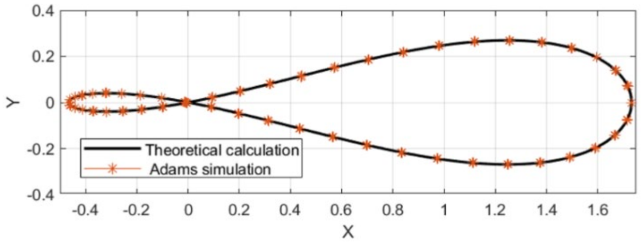
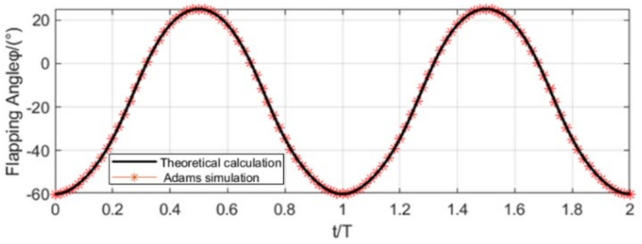


Figure 6. Adams model of the flapping mechanism

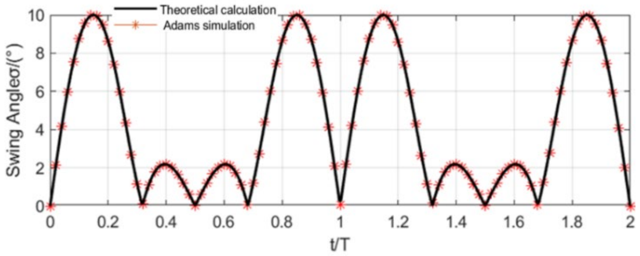
Apply a torque to the prime mover and turn it 720° (two cycles) to observe the trajectory and output angle, and then compare with the theoretical calculated values. The results were shown in Figure 7: in terms of kinematic characteristics, the trajectory of the wing tip had an “8” shape, which was consistent with the theoretically calculated trajectory; the output angles were also consistent with the theoretically calculated value. It can be proved that the theoretical analysis was correct.



(a) Wingtip trajectory.



(b) Flapping angle.



(c) Swing angle

Figure 7. Comparison between theoretical calculation and ADAMS simulation.

7. Analysis of results

Based on the mechanism proposed by Chen, the main parameters of the FWMAV were optimized using non-linear programming functions in MATLAB. The key findings from the present calculations are as follows.

1) Assume that the distance of the Flapping-Wing plane from the spherical joint bearing is 1 and then the length ratio of the critical part of the mechanism is

$$L_1 : L_2 : L_3 : L_4 = 0.5857 : 0.5135 : 2.9189 : 2.2860$$

2) The mechanism has an upward Flapping angle of 60°, a downward Flapping angle of 24.99° and a swing angle of 10.71°, which corresponds to the actual flight conditions of the insect.

3) With a minimum transmission angle of 79.87°, the mechanism has good force transmission properties.

8. Conclusion

The single-degree-of-freedom Flapping-Wing mechanisms do not simulate the actual flight of creatures satisfyingly. This paper presented an optimized single-degree-of-freedom mechanism that generated Flapping-Swing motion like an insect, whose wingtip exhibited an “8” shape. In the future, more practical factors such as the selection of materials, control and stabilization will be taken into account.

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