An optimization on single-crank-double-rocker flapping wing mechanism

Chao Wang, Chaoying Zhou, Xingwei Zhang, Cong Liu
Department of Mechanical Engineering and Automation
Shenzhen Graduate School, Harbin Institute of Technology, Xili Shenzhen University Town
Shenzhen 518055, China
cwang1117@gmail.com&cyzhou@hit.edu.cn

***Abstract*—A single-crank-double-rocker mechanism is used to realize the flapping motion of Micro flapping aerial vehicle. However, this vehicle often pitches toward left or right and crashes during flight which mainly caused by the incomplete symmetry of wings movement. To solve this problem, mathematical models of the flapping angle and angular velocity of two wings are established, respectively. An optimal design based on the objective function is carried out under some mechanics, bionics and aerodynamics restraint condition. To verify the mathematical model, then, the mechanism is also analyzed in ADAMS environment. The results indicate that the optimization can remarkably improve the symmetry of flapping wings movement.**

key words; micrio flapping air vehicle; mathematical modeling; crank-and-rocker mechanism

I. INTRODUCTION

Micro flapping aerial vehicles (MFAV) are defined as flapping flight vehicles with smaller than 15cm in size, less than 100g in weight and being developed in both military and scientific fields, such as reconnoitering in confined spaces, communications relay, signal interference and so on [1]. MFAV can provide the forces for hovering and forward function just by the flapping motion, which is different from the fixed wing and rotary wing vehicles; Moreover, they have the ability to keep stable hover, easy maneuverable and high power efficiency in low speed flight [2-5]. A detailed discussion of the future utility of MFAV and the advantages of considering insect-like flapping wing propulsion has been presented [6,7]. However, there are still some problems haven't been solved; one of them is the driving system.

As a key section of MFAV design, the driving mechanism provides a determined flight pattern for the flapping wings. Based on the analysis and simplification of biological flight patterns, the driving mechanism can be mainly divided into two categories [8]. One is single degree of freedom mechanism which can achieve the upper and lower flapping flight easily. The other is multiple degrees of freedom mechanism which can achieve a form of complex motion, such as reversed and folding action. However, the multiple degrees of freedom mechanism is a spatial mechanism suffering high-frequency flutter, it must be accompanied by another set of institutions which will extremely negative for the flapping-wing flight. On the contrary, by means of suitable wing-type structure and material, single degree of freedom mechanism can achieve certain amount of reverse movement easily [9]. Therefore, the single degree of freedom mechanism is chosen for current mechanism in this paper.

Single-crank-double-rocker mechanism is the simplest realization of flapping motion with high efficiency, light weight, easy miniaturization, etc. However, during the flight, it often tilts toward the left or the right and even falls off, these disadvantages are mainly caused by the incomplete symmetry of the wings movement. To solve this problem, Mathematical models of the flapping angle and angular velocity of two wings have been established, and then an optimal design for improving the symmetry of the flapping motion has been carried out in this paper.

II. MATHEMATICAL MODELING FOR OPTIMIZATION

The schematic of driving mechanism is shown in Fig. 1. γ is the stagger angle, l_1 is the crank length, l_2 is the linkage length, l_3 is the rocker length, l_4 is the distance between the fulcrum O and O_1, and α is the angle between the crank and OO_1.

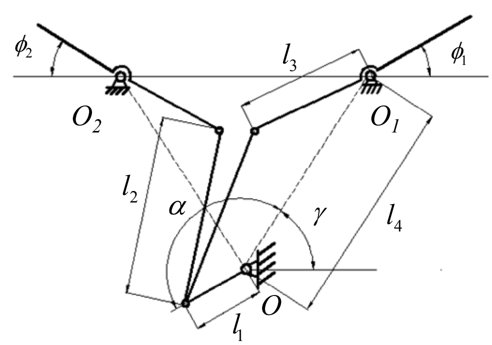


Figure 1. The schematic of driving mechanism.

The angular velocity of crank can be written as follows:

$$\omega = \frac{\pi n_1}{30i} \tag{1}$$

where n_1 is the motor speed, i is the total transmission ratio.

The flapping angle and angular velocity of the right rocker are denoted by $\phi_1(\alpha)$, $\omega_1(\alpha)$, respectively, while the flapping angle and angular velocity of the left rocker are denoted by $\phi_2(\alpha)$, $\omega_2(\alpha)$, respectively. Using the method of instantaneous center of velocity, the flapping wing angle and angular velocity of two wings can be obtained. During one period of motion, $\Delta\phi(\alpha)$ denotes the difference of two wings

978-0-7695-4281-2/10 $26.00 © 2010 IEEE
DOI 10.1109/ICGEC.2010.90

flapping angle, while $\Delta\omega(\alpha)$ denotes the difference of two wings angular velocity, and they can be expressed as follows:

$$\begin{aligned}\Delta\phi(\alpha) &= \phi_1(\alpha) - \phi_2(\alpha)\\ &= \left(\arccos\frac{l_3^2 + l_6^2 - l_2^2}{2l_3l_6} + M_2\arccos\frac{l_4^2 + l_6^2 - l_1^2}{2l_4l_6}\right) - \\ &\left(\arccos\frac{l_3^2 + l_5^2 - l_2^2}{2l_3l_5} + M_1\arccos\frac{l_4^2 + l_5^2 - l_1^2}{2l_4l_5}\right)\end{aligned} \tag{2}$$

$$\begin{aligned}\Delta\omega(\alpha) &= \omega_1(\alpha) - \omega_2(\alpha)\\ &= \frac{\omega}{l_4}\left(\frac{l_1\sin\beta_1}{\sin(\alpha+\beta_1)} - 1\right) - \frac{\omega}{l_4}\left(\frac{l_1\sin\beta_2}{\sin(\alpha - B - \beta_2)} + 1\right)\end{aligned} \tag{3}$$

where

$$B = 180° - 2\gamma \tag{4}$$

$$l_5 = \sqrt{l_1^2 + l_4^2 - 2l_1l_4\cos\alpha} \tag{5}$$

$$l_6 = \sqrt{l_1^2 + l_4^2 - 2l_1l_4\cos(\alpha - B)} \tag{6}$$

$$\beta_1 = arc\cos\frac{l_2^2 + l_5^2 - l_3^2}{2l_2l_5} + M_1 arc\cos\frac{l_1^2 + l_5^2 - l_4^2}{2l_1l_5} \tag{7}$$

$$\beta_2 = arc\cos\frac{l_2^2 + l_6^2 - l_3^2}{2l_2l_6} + M_2 arc\cos\frac{l_1^2 + l_6^2 - l_4^2}{2l_1l_6} \tag{8}$$

$$(M_1, M_2) = \begin{Bmatrix} (+1,+1) & 0 \le \alpha < B \\ (+1,-1) & B \le \alpha < 180^\circ \\ (-1,-1) & 180^\circ \le \alpha < 180^\circ + B \\ (-1,+1) & 180^\circ + B \le \alpha < 360^\circ \end{Bmatrix} \tag{9}$$

III. OPTIMIZATION PROCESS

A. Optimization Objective Function

In the second part, mathematical models have been established by setting α as a variable corresponding to the location of the crank, and α changes from 0 to 2π during every revolution of the crank. Considering that the purpose of optimization is the symmetry of two wings motion, which means the smallest difference of the flapping angle as well as the angular velocity of two wings. Therefore, α is discretized into a number of values between 0 and 2π, where n denotes the total numbers. The sum of the absolute value for the $\Delta\phi(\alpha)$ and $\Delta\omega(\alpha)$ should be the objective function showing in (10).

$$\begin{aligned} Min: f_1 &= \sum_{i=1}^{n}|\Delta\phi| = \sum_{i=1}^{n}|\Delta\phi_1 - \Delta\phi_2| \\ f_2 &= \sum_{i=1}^{n}|\Delta\omega| = \sum_{i=1}^{n}|\Delta\omega_1 - \Delta\omega_2| \end{aligned} \tag{10}$$

B. Optimization Parameters

According to the objective function of optimization and the actual situation, the following design variables are defined as the optimization parameters: linkage length l_2, rocker length l_3, fulcrum distance l_4 and the stagger angle γ. As we know, the shorter the crank, the smaller the amplitude of $\Delta\phi(\alpha)$ and $\Delta\omega(\alpha)$, but more driving torque will be needed. So in this paper, the length of the crank has been set as a constant.

C. Constrains

Mechanics conditions are defined as follows:

$$20\text{mm} \le l_2 \le 45\text{mm} \tag{11}$$

$$15\text{mm} \le l_3 \le 25\text{mm} \tag{12}$$

$$20\text{mm} \le l_4 \le 50\text{mm} \tag{13}$$

$$50° \le \gamma \le 60° \tag{14}$$

$$l_1 + l_2 \le l_3 + l_4 \tag{15}$$

Minimum transmission angle conditions are defined as follows:

$$\text{Min}(\theta_1, \theta_2) \ge 40° \tag{16}$$

where

$$\theta_1 = 57.3 \times arc\cos\frac{l_2^2 + l_3^2 - (l_4 - l_1)^2}{2l_2l_3} \tag{17}$$

$$\theta_2 = 180^\circ - 57.3 \times arc\cos\frac{l_2^2 + l_3^2 - (l_4 + l_1)^2}{2l_2l_3} \tag{18}$$

When the rocker moves to the highest position, the angle between the horizontal line and the rocker is set to be ψ_1, while the rocker moves to the lowest position, the angle is set to be ψ_2, then ψ_1=Max($\phi(\alpha)$), ψ_2=Min($\phi(\alpha)$).

Based on the statistical laws of bionics: the amplitude of birds flapping wing angle $\psi = \psi_1 - \psi_2$ usually is not less than 50°, so the bionics conditions can be defined as follows:

$$\psi > 50° \tag{19}$$

D. Optimization Method

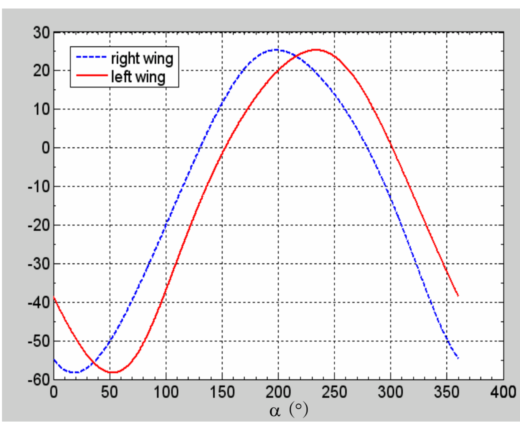
For the nonlinear function optimization with multi-objective and multi-variable, we usually use linear weight method to construct a comprehensive evaluation function:

$$f(\alpha)=c_1 f_1(\alpha)+c_2 f_2(\alpha) \tag{20}$$

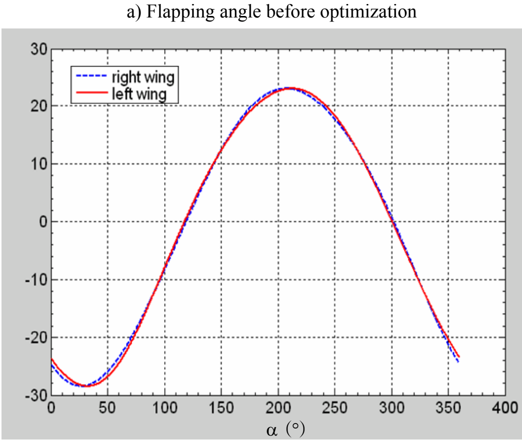
In (20), the weight coefficients c_1 and c_2 shall meet the formatting (x, 1-x), [x = 0.1, 0.2,…1.0], in addition, the selection of weight coefficients shall according to their effect on the symmetry of the movement, through the continuous experiments and computations, we suppose weight coefficients c_1 and c_2 have the same weight, and the objective function can be simplified as single-objective nonlinear optimization problem with multi-variable. In this paper, the interval search method has been used to realize the optimization.

IV. OPTIMIZATION RESULTS

Before the optimization, the initial design variables are l_1=10mm, l_2=33mm, l_3=15mm, l_4=35mm and γ=54°, after the optimization, the optimized design variables are: l_1=10mm, l_2=40mm, l_3=23mm, l_4=45mm and γ=60°. The flapping angle and the angular velocity of the two wings before and after the optimization are showed in Fig. 2 and Fig. 3. The key parameters for the mechanism before and after optimization are compared in Table. 1.



a) Flapping angle before optimization



b) Flapping angle after optimization

Figure 2. The comparison of flapping angle before and after optimization.

TABLE I THE COMPARISON OF KEY PARAMETERS BEFORE AND AFTER OPTIMIZATION

Parameters	Before Optimization	After Optimization
Max $\lvert\Delta\phi\rvert$ (°)	17.58	1.01
Max $\lvert\Delta\omega\rvert$ (rad/s)	41.20	3.06
ψ(°)	83.64	51.55
Minimum transmission angle (°)	45.90	60.58

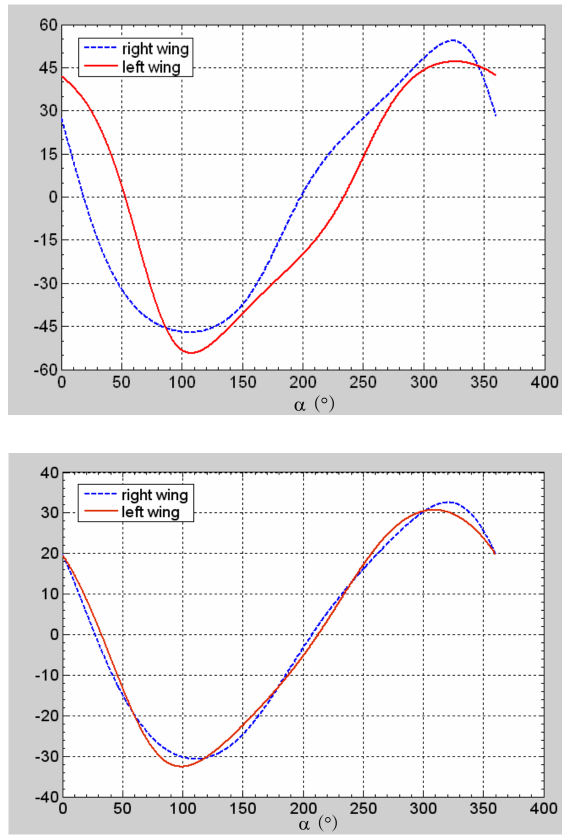


Figure 3. The comparison of the angle velocity before and after optimization.

As shown in the above figures and table, the following conclusion can be achieved through the comparison of the results before and after optimization:

1) After the optimization, the maximum drop of $\lvert\Delta\phi\rvert$ and $\lvert\Delta\omega\rvert$ are 94.25% and 92.57% respectively, showing that the optimized size achieves the purpose of improving the movement symmetry of flapping wings.

2) The minimum transmission angle has increased nearly 15°; the greater the transmission angle, the better the transmission effect, and the transmission will be more flexible and more efficient.

V. ADAMS MODELING

Based on the optimized size, the mechanism model has been built in ADAMS which is shown in Fig. 4. The curve chart for each parameter is available as one cycle kinematics simulation is finished. In order to verify the mathematical model, the curve chart obtained from the mathematical model has been compared with the ADAMS simulation.

Fig. 5 and Fig. 6 illustrate the optimized simulation of flapping angle and angular velocity in ADAMS.

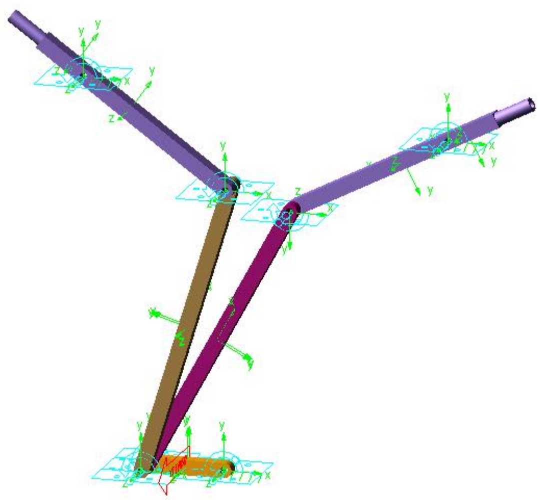


Figure 4. ADAMS modeling diagram.

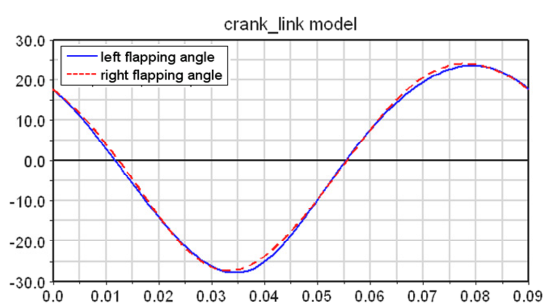


Figure 5. The optimized simulation of angle curve.

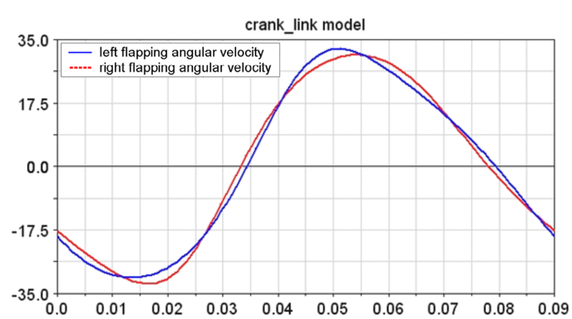


Figure 6. The optimized simulation of angular velocity curve.

The motor speed is 20000r/min, while the transmission ratio is 30. Thus, it will cost 0.09s for a cycle of motion; the horizontal axis of mathematics model is consistent with the simulation curves. The figure has shown that both the mathematical modeling and the simulation in ADAMS can get exactly the same curves with the same parameters, which means that both the mathematical modeling and simulation modeling are correct.

VI. CONCLUSION

In spite of the disadvantages mainly caused by the incomplete symmetry of the wings movement, single-crank-double-rocker mechanism is the simplest way to realize the flapping motion with high efficiency, light weight and easy miniaturization, etc.

Mathematical models of the flapping angle and angular velocities of the two wings have been established which provide theoretical basis and good reference for the similar mechanism design. With the help of simulation in ADAMS, the model has been verified. The amplitude values of the difference between two wings flapping angle as well as angular velocity have become significantly lower. The current model has improved the symmetry of the flapping motion greatly.

ACKNOWLEDGMENT

The work described in this paper was supported by a grant from National Natural Science Foundation of China (Project number No. 90715031). The financial support is gratefully acknowledged.

REFERENCES

[1] M. M. James, S. F. Michael, "Micro Air Vehicles-Toward a New Dimension in Flight," US DAPPA/TTO Report, 1997

[2] C. P. Ellington, "The Novel Aerodynamics of Insect Flight: Applications to Micro Air Vehicles," Journal of Experimental Biology, 1999, pp. 3439-3448.

[3] A. P. Willmott, C. P. Ellington, "The Mechanics of Flight in the Hawkmoth Manduca Sexta, I. Kinematics of Hovering and Forward Flight," Journal of Experimental Biology, 1997, pp. 2705-2722.

[4] C. van den Berg, C. P. Ellington, "The Vortex Wake of a 'Hovering' Model Hawkmoth," Philosophical Transactions of the Royal Society B: Biological Sciences, 1997, 352(1351): pp. 317.

[5] C. van den Berg, C. P. Ellington, "The Three-Dimensional Leading-Edge Vortex of a 'Hovering' Model Hawkmoth," Philosophical Transactions of the Royal Society B: Biological Sciences, 1997, 352(1351): pp. 329.

[6] R. Zbikowski, ''Flapping Wing Technology,'' European Military Rotorcraft Symposium, Shrivenham, UK, 2000, pp. 1–7.

[7] R. Zbikowski, ''Flapping Wing Technology,'' European Military Rotorcraft Symposium, Shrivenham, UK, 2000, pp. 1–7.

[8] R. S. Fearing, K. H. Chiang, M. H. Dickinson, "Wing Transmission for a Micromechanical Flying Insect," IEEE Internation Coference on Robotics and Automation, New York, 2000,Vol.2, pp. 1509-1516.

[9] M. H. Dickinson, F. O. Lehmann, "Wing Rotation and the Aerodynamics Basis of Insect Flight," Science, 284, 1999, pp. 1954-1960.