Dynamic Analysis of the Flapping Mechanism of Flapping Wing Aircraft

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Abstract. In order to improve the design level of bionic flapping-wing aircraft, it is necessary to find out the influence of load undulating moment on the motor under the action of air undulating moment. This paper takes flapping-wing aircraft with a crank and rocker mechanism as an example. Firstly, the kinematics model of the flapping mechanism is established, and the relative motion parameters are obtained. Secondly, the dynamic model of flapping-wing aircraft is deduced by using Lagrange dynamic equation. Then, based on the strip method, the aerodynamic moment of air to flapping aircraft is calculated, and the obtained aerodynamic moment is substituted into the dynamic model of the system, to calculate the torque fluctuation on the crank during the flapping flight of flapping aircraft by MATLAB. Finally, in order to verify the correctness of the model, ADAMS software is used to simulate the system, and the simulation results are consistent with the calculated results of the model, thus proving the correctness of the model.

1. Introduction
The Micro-Fly-Winged Aircraft (FMAV) is a new concept aircraft that mimics the flight of birds or insects. Compared with fixed-wing and rotor-wing aircraft, the main feature of the tiny flap-wing aircraft is that it combines lifting, hovering and propulsion functions into a flapping wing system that can travel long distances with very little energy and at the same time has strong flexibility. Studies have shown that flapping wings have advantages over fixed-wing and rotor-wing.

In order to realize the bionic function requirements of the flapping wing aircraft, it is necessary to design the flight realization scheme of the flapping wing aircraft, and determine the overall and partial design schemes for realizing the bionic functions of each part, and the design focus of the flapping wing aircraft is on the fluttering scheme. At the same time, in order to analyze and evaluate the performance of the flapping wing mechanism, it is necessary to analyze the kinematics of the flapping wing aircraft and analyze the parameters such as angular displacement, angular velocity and angular acceleration of the flapping wing mechanism. These motion parameters are the fundamental basis for evaluating and analyzing the performance of the mechanism. On the other hand, when flying a flying wing aircraft, vibration, noise, and instability are often caused by the inertia of the flapping mechanism and the periodically changing aerodynamic force acting on the flapping wing. Kinetic analysis has important implications.
At present, the commonly used driving schemes include a crank rocker mechanism, a crank slider mechanism, a cam rocker mechanism, and space 7-bar eight hinge mechanism. However, compared with other flapping-wing drive mechanisms, the crank rocker mechanism is the most suitable mechanism for miniaturization. Therefore, the crank rocker mechanism is used as the flapping mechanism of the flapping wing aircraft, and kinematics and dynamics analysis are carried out.

2. Kinematic analysis of the flapping mechanism

2.1. Establishment of flutter mechanism model

In this paper, the geese are used as a prototype for bionic design. In order to facilitate the analysis of the flapping mechanism, the flapping mechanism is simplified according to the fluttering of the wings when the geese fly, as shown in Figure 1 (a) because the mechanism used is a double crank mechanism. The organization is entirely symmetrical about a plane, so the only one-sided mechanism is analyzed for simplifying the analysis, as shown in Figure 1(b).

![Figure 1](image)

Figure 1. (a) Sketch of the flapping wing mechanism; (b) Schematic diagram of the single-sided flapping mechanism.

In the figure, $l_0$ is the distance between the frame O and the frame OC; $l_1$ is the length of the crank OA; $l_2$ is the length of the link AB; $l_3$ is the length of the BC; and $l_4$ is the length of the BD. $\theta_0$ is the installation angle of the mechanism; $\theta_1$ is the instantaneous angular velocity through which the crank turns; $\theta_2$ is the instantaneous angular velocity through which the link rotates; $\theta_3$ is the instantaneous flapping angle of the rocker.

2.2. Analysis of the position of the flapping mechanism

In order to analyze the motion of the flapping mechanism, a vector diagram of the flapping mechanism is established in the Cartesian coordinate system, as shown in Fig. 3. It can be seen from Figure 2 that the plane four-bar mechanism OABC determines the instantaneous angle of the flapping mechanism rocker, and the closed-loop vector equation (angular displacement equation) of the mechanism is:

$$l_1 + l_2 = l_0 + l_3$$

(1)

The mechanism can satisfy the vector equation at any position of the mechanism motion as long as the mechanism meets the geometric assembly conditions. Write the formula (1) into the component form, and obtain the component form equation of the angular displacement of the flapping mechanism :

$$\begin{align*}
l_1 \cos \theta_1 + l_2 \cos \theta_2 &= l_0 \cos \theta_0 + l_3 \cos \theta_3 \\
l_1 \sin \theta_1 + l_2 \sin \theta_2 &= l_0 \sin \theta_0 + l_3 \sin \theta_3
\end{align*}$$

(2)
In order to solve the formula (2), connect AC in Figure 3, which can be obtained from the geometric relationship and the angle relationship:

\[ l_{AC}^2 = l_1^2 + l_2^2 - 2l_1l_2 \cos(\theta_1 - \theta_0) \]  \hspace{1cm} (3)

\[ \beta_0 = \arcsin\left(\frac{l_1}{l_{AC}} \sin(\theta_1 - \theta_0)\right) \]  \hspace{1cm} (4)

\[ \beta_i = \arccos\left(\frac{l_{AC}^2 + l_3^2 - l_2^2}{2l_1l_{AC}}\right) \]  \hspace{1cm} (5)

\[ \theta_3 = \pi - \beta_0 - \beta_i + \theta_0 \]  \hspace{1cm} (6)

Bringing the formula (6) back to the formula (2), the instantaneous angle of the connecting rod AB can be obtained as follows:

\[ \theta_2 = \arcsin\left(\frac{l_0 \sin \theta_0 + l_1 \sin \theta_1 + l_2 \sin \theta_2}{l_2}\right) \]  \hspace{1cm} (7)

According to Figure 2, the centroid coordinates of the connecting rod AB can be obtained as follows:

\[
\begin{align*}
x_{c2} &= l_1 \cos \theta_1 + \frac{l_2}{2} \cos \theta_2 \\
y_{c2} &= l_1 \sin \theta_1 + \frac{l_2}{2} \sin \theta_2
\end{align*}
\]  \hspace{1cm} (8)

According to the simplified diagram of the single-side flapping mechanism, refer to the relevant data and take the crank rotation frequency \( f = 2 \text{HZ} \). The parameters of each component are shown in Table 1:
Table 1. Flutter mechanism length size parameters and values

| Parameter | Value   |
|-----------|---------|
| L0        | 55mm    |
| L1        | 20mm    |
| L2        | 45mm    |
| L3        | 50mm    |
| L4        | 230mm   |

2.3. Flapping mechanism speed analysis

In order to obtain the speed of the flapping mechanism linkage and the rocker, the component equation (2) of the angular displacement of the flapping mechanism is differentiated from the time to obtain the velocity equation:

\[
\begin{align*}
-l_1 \sin \theta_1 \dot{\theta}_1 - l_2 \sin \theta_2 \dot{\theta}_2 &= -l_3 \sin \theta_3 \dot{\theta}_3 \\
l_1 \cos \theta_1 \dot{\theta}_1 + l_2 \cos \theta_2 \dot{\theta}_2 &= l_3 \cos \theta_3 \dot{\theta}_3
\end{align*}
\]  

(9)

The resulting formula (8) is organized and represented by a matrix as:

\[
\begin{bmatrix}
-l_2 \sin \theta_2 & l_1 \sin \theta_1 \\
l_2 \cos \theta_2 & -l_3 \cos \theta_3
\end{bmatrix}
\begin{bmatrix}
\dot{\theta}_2 \\
\dot{\theta}_3
\end{bmatrix}
= 
\begin{bmatrix}
l_1 \sin \theta_1 \dot{\theta}_1 \\
l_3 \cos \theta_3 \dot{\theta}_3
\end{bmatrix}
\]  

(10)

The angular velocity of the flapping mechanism linkage and the rocker is solved by equation (9):

\[
\begin{align*}
\dot{\theta}_2 &= \frac{-l_1 \sin (\theta_1 - \theta_2)}{l_2 \sin (\theta_2 - \theta_3)} \dot{\theta}_1 \\
\dot{\theta}_3 &= \frac{+l_1 \sin (\theta_1 - \theta_3)}{l_3 \sin (\theta_2 + \pi - \theta_3)} \dot{\theta}_1
\end{align*}
\]  

(11)

The equation (8) is used to find the first derivative of the time, and the centroid velocity of the connecting rod AB is obtained as follows:

\[
\begin{align*}
x_{c2} &= -l_1 \dot{\theta}_1 \sin \theta_1 - \frac{1}{2} l_2 \dot{\theta}_2 \sin \theta_2 \\
y_{c2} &= l_3 \dot{\theta}_1 \cos \theta_1 + \frac{1}{2} l_2 \dot{\theta}_2 \cos \theta_2
\end{align*}
\]  

(12)

According to the above model, the parameters of Table 1 are substituted into the above model, and the crank angular velocity \( \alpha_t (\theta_1) \) is taken as 4 rad/s angular velocity of the connecting rod and the rocker in one cycle is calculated by using MATLAB, and the angular velocity curve is plotted as shown in Figure 3 and Figure 4.
2.4. Acceleration analysis of fluttering mechanism

In order to obtain the angular acceleration of the flutter mechanism linkage and the rocker, the component form equation (2) of the angular displacement of the flapping mechanism is differentiated twice to obtain the angular velocity equation:

$$\begin{align*}
\begin{bmatrix}
-l_1 \sin \theta_2 & l_3 \sin \theta_3 & \ddot{\theta}_2 \\
 l_2 \cos \theta_2 & -l_3 \sin \theta_3 & \ddot{\theta}_3 \\
\end{bmatrix}
& + \begin{bmatrix}
-l_1 \cos \theta_1 & -l_2 \cos \theta_2 & l_3 \cos \theta_3 \\
-l_1 \sin \theta_1 & -l_2 \sin \theta_2 & l_3 \sin \theta_3 \\
\end{bmatrix}
\begin{bmatrix}
\dddot{\theta}_1 \\
\dddot{\theta}_2 \\
\dddot{\theta}_3 \\
\end{bmatrix}
= \begin{bmatrix}
-l_1 \sin \theta_1 \dddot{\theta}_1 \\
-l_2 \cos \theta_2 \dddot{\theta}_2 \\
\end{bmatrix}
\end{align*}$$

Solve the formula (11) to obtain the angular velocity of the flapper linkage and the rocker:

$$\begin{align*}
\ddot{\theta}_2 &= \frac{-l_1 \cos (\theta_1 - \theta_2) \dddot{\theta}_1 - l_2 \cos (\theta_2 - \theta_3) \dddot{\theta}_2 + l_3 \dddot{\theta}_3 - l_1 \sin (\theta_1 - \theta_2) \dddot{\theta}_1}{l_2 \sin (\theta_2 - \theta_3)} \\
\ddot{\theta}_3 &= \frac{-l_1 \cos (\theta_1 - \theta_2) \dddot{\theta}_1 + l_3 \cos (\theta_2 - \theta_3) \dddot{\theta}_3 - l_2 \dddot{\theta}_2 + l_1 \sin (\theta_2 - \theta_3) \dddot{\theta}_1}{l_2 \sin (\theta_2 - \theta_3)}
\end{align*}$$

(14)
The first derivative of the equation (12) is obtained for the time, and the centroid acceleration of the connecting rod AB is obtained as follows:

\[
\begin{align*}
\dddot{x}_{c2} &= -l_1 \dddot{\theta}_1 \sin \theta_1 - l_1 \dot{\theta}_1^2 \cos \theta_1 - \frac{l_2}{2} \dddot{\theta}_2 \sin \theta_2 - \frac{l_2}{2} \dot{\theta}_2^2 \cos \theta_2 \\
\dddot{y}_{c2} &= l_1 \dddot{\theta}_1 \cos \theta_1 - l_1 \dot{\theta}_1^2 \sin \theta_1 + \frac{l_2}{2} \dddot{\theta}_2 \cos \theta_2 - \frac{l_2}{2} \dot{\theta}_2^2 \sin \theta_2
\end{align*}
\]  

(15)

The parameters in Table 1 and the angular displacement and angular acceleration values calculated in Sections 1.2 and 1.3 are substituted into the above model, and MATLAB calculates the angular acceleration values of the connecting rod and the rocker in one cycle. Moreover, plot the angular acceleration of the two with time, as shown in Figure 5 and Figure 6.

**Figure 5.** Link angular acceleration curve

**Figure 6.** Rocker acceleration curve

3. ADAMS simulation analysis

The ADAMS software is a mechanical system dynamics analysis software developed by the former American Mechanical Power Company. ADAMS software can simulate software for real structural motion relationships through 3D modeling, adding component constraints, determining component materials, and adding motion relationships. Kinematics and dynamics analysis can be performed on the designed mechanical mechanism to obtain the motion parameters and stress conditions of each component to verify the correctness of the design structure and theoretical calculation.
3.1. Drive Mechanism ADAMS Motion Simulation

The parameters of the individual members of the crank rocker mechanism obtained above are taken as design parameters. Establish a physical simulation model of the flapping mechanism. The specific steps are as follows: After running ADAMS, create a new file and set the modeling area and basic unit. In the work area, first take the following 4 points O (0,0), A (20,0), B (-17,25), C (27.5,48); then, starting from the (0, 0) point, establish a A crank with a length of 20, and then a pinhole of the crank ((-17, 25) direction, establish a link with a length of 45. Then build a length of 50 from the end of the link to the (27, 48) direction. The simulation model of the drive mechanism has been initially established, as shown in Figure 7:

![Figure 7. Drive Mechanism Simulation Model](image)

Then set the movable hinge constraint at the joint of the crank, connecting rod and rocker. At the joint between the crank and the frame, add a rotary drive with a driving speed of \( \frac{4\pi \text{ rad}}{\text{s}} \). At this time, the rotational motion period of the crank is \( T = 0.5 \text{ s} \), frequency \( f = 2 \text{ Hz} \). As shown in Figure 8.

![Figure 8. Adding the driving mechanism simulation model](image)

Establish the measurement of the rocker angle, angular velocity, and angular acceleration, then set the number of simulation steps to 500 steps, and the simulation time is 1 s, that is, simulate the two flapping cycles. The angular displacement, angular velocity, and angular acceleration of the drive mechanism rocker in two cycles are shown in Figure 9, Figure 10 and Figure 11. Compared with the rocker displacement and angular velocity calculated by MATLAB in Section 3, the angular acceleration curves in Figure 5, Figure 7, and Figure 9 show that the two are in harmony with each other, which proves the correctness of the kinematics analysis of the model.
3.2. Fluctuating mechanism ADAMS dynamics simulation

The kinematics simulation of the model is carried out in Section 3.1. The analysis results show that the simulation results are consistent with the theoretical calculation results in Section 2, indicating that the modeling is correct and dynamic simulation can be performed.
Since the aerodynamic forces generated by the flutter-wing aircraft flight are continually changing, the aerodynamic loading is the primary problem in the dynamic simulation analysis of the flapping-wing aircraft model.

Firstly, the aerodynamic data calculated by the previous MATLAB is derived in .txt format; the derived aerodynamic data cannot be directly introduced into the ADAMS. First, the initial value of the aerodynamic data does not correspond to the initial position of the crank of the model. Because ADAMS has specific requirements on the data format in the text file, the aerodynamic data must be adjusted accordingly before being introduced into ADAMS. So make a little adjustment to the derived aerodynamic torque. Finally, the numerically adjusted and unit-converted aerodynamic data is imported into the ADAMS to generate aerodynamic force and loaded into the aerodynamic center. Further, the motor drive angular velocity is 4 rad/s, and the simulation time is 1 s to simulate the flapping-wing aircraft. The balance moment diagram of the crankshaft of the flapping mechanism is obtained, as shown in Figure 12.

![Figure 12. ADAMS simulation crank balance torque curve.](image)

The comparison chart shows that the theoretical calculation results and the simulation result curves are the same, indicating that the dynamic model is correct in Section 3. They are also seen in Figure 20. When the flapping-wing aircraft is flying, the balance moment on the crankshaft fluctuates continuously, and the maximum torque is 0.44 N.m.

The fluctuating torque will inevitably affect the motor. To reduce this effect, consider adding a spring to the system.

4. Conclusion
Under the effect of uniform driving of the motor, considering the influence of the aerodynamic moment force of the wing and the moment of inertia of the mechanism, the crank can not maintain a constant torque, which will inevitably affect the motor. Firstly, through the kinematics analysis of the flapping mechanism of the flapping wing aircraft, the mathematical model of the flapping mechanism motion is established, which provides the theoretical design basis for the design of the same type of driving mechanism. Then the dynamic model of the flapping mechanism of the flapping wing aircraft is established by using the Lagrangian dynamic equation. Based on the Delaurier strip theory, the aerodynamic moment estimation model of the flapping wing aircraft is established, and MATLAB calculates the aerodynamic moment of the flapping wing. The aerodynamic torque is substituted into the dynamic model to calculate the fluctuation of the crankshaft balance torque. Finally, in order to verify the accuracy of the model, kinematics and dynamics simulations were performed using ADAMS software.
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