Dynamic analysis of piezoelectrically driven flapping wing

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Abstract. The micro flapping wing using the traditional flapping wing mechanism has the disadvantages of low aerodynamic efficiency and high energy consumption. The bionic flapping wings driven by piezoelectric materials can effectively combine the two main systems of flapping wings and wings. It not only has the task of reducing weight but also has the characteristics of strong deformation ability, high aerodynamic efficiency, and low energy consumption of mechanism. The structure simulation of piezoelectrically driven bionic flapping wing was carried out to use aerodynamic experimental data of the same size of flapping wing. The piezoelectrically driven bionic flapping wing was developed by using the simulation results. The studies show flapping frequency of bionic flapping wing has been improved obviously after using the piezoelectric actuator. The piezoelectric patches can effectively control the wing bending and torsion deformation, which is helpful to improve aerodynamic efficiency of the flapping wing.

1. Introduction
Flapping wing aircraft is a new concept aircraft that generates lift and thrust by flapping up and down the wing. Aerodynamic research results show that flapping-wing flight mode of MAV with main dimension less than 15cm has larger lift-to-drag ratio, stronger anti-disturbance capability and more flexible maneuverability than fixed wing and rotor flight mode [1].

The flapping mechanism of conventional flapping wing has low aerodynamic efficiency, which is caused by the failure of this mechanism to realize high frequency flapping. Compared with other driving mechanisms, the piezoelectric actuator has unique advantages: wide working frequency range, large dynamic range, fast frequency response speed, high sensitivity, good temperature stability (-20℃ ~ 150℃), light weight and simple structure, which can be pasted on the surface of the structure or coupled into the structure through certain technological measures. In particular, the development of sacrificial layer etching technology provides a technical background for the application of piezoelectric actuators in flapping-wing aircraft [2].

At present, many institutions and teams are still in the theoretical exploration stage for the research of piezoelectric-driven new flapping mechanism. The representative ones can be listed as follow: Zhang Xijin of Northwestern University of Technology studied the structural design and dynamic characteristics of electromagnetic vibration flapping-wing micro-mechanism, analyzed the dynamic response of the system under different electromagnetic forces, and obtained the natural frequency of the system [3]; Hou Yu of Northwest University of Technology designed a piezoelectric-driven two-degree-of-freedom flapping mechanism based on the principle of rhythmic movement of insect flapping wings [4]. Wang Xin of Nanjing University of Aeronautics and Astronautics studied the
bionic flexible flapping wing mechanism driven by piezoelectric bimorphs. A flapping wing system is designed in which piezoelectric bimorph drives flexible double rocker mechanism to enlarge displacement and drives bionic wings to flap [5].

Mentor concept machine was developed by SRI and Toronto University [6]. The wing is driven by an electrostrictive polymer EPAM. EPAM shrinks and elongates by rapidly changing the voltage value. The device is especially suitable for fast swinging motion, such as flapping wing motion. Hsien-ChunChung of Cranfield University in UK has conducted simulation research on flapping-wing aircraft using piezoelectric materials [7]. Hsien-ChunChung conducted simulation research on wing flapping from different angles such as flapping phase and frequency. NquvenQV of Konkuk University in South Korea combined simulation and experiment to study the aerodynamic force and flapping characteristics of bionic flapping wing with piezoelectric actuator [8]. Piezoelectric actuators can be used to develop insect-scale micro-aircraft [9]. SujoyMukherjee of Bangalore University in India studied the dynamics of flapping wings of dragonfly with piezoelectric actuators [10]. AdamGrantCox of Vanderbilt University in the United States has studied the lift and power characteristics of hovering flapping wings using piezoelectric actuators [11].

The research in this paper is based on the analysis of the flapping wing driving principle of piezoelectric actuator, combined with the existing experimental data of aerodynamic force and inertial force of flapping wing of the same size, through PCL parametric structural simulation, the dynamic characteristics of flapping wing structure of piezoelectric actuator are simulated, which provides theoretical guidance for the development of flapping wing of piezoelectric actuator.

![Figure 1. Micromechanical Flying Insect.](image_url)

2. Piezoelectric actuator flapping wing

2.1. Driving principle

The wing using piezoelectric actuator (as shown in fig. 2) is a new concept wing structure that uses piezoelectric actuator (PZT) to drive the wing to generate active deformation. Piezoelectric materials are arranged at the root of the wing in a glued parallel manner. This design can make use of the in-plane expansion and contraction characteristics of piezoelectric patches. In order to improve the structural characteristics of the wing, this structure can drive the piezoelectric actuators of the two wings to realize the high frequency flapping of the wing on the premise of following the resonance principle. As shown in Fig.2, this structure can adjust the input voltage to cause the flapping amplitudes of the two wings to be different so as to change the aerodynamic force on the wing.

The advantages of this kind of flapping mechanism are as follows: (1) high frequency flapping can be realized by adopting voltage drive with appropriate frequency and system resonance (larger flapping angle can be realized with smaller drive voltage); (2) the flapping angle can be adjusted by changing the amplitude of the driving voltage, which is convenient for flapping-wing aircraft control and attitude change; (3) it is easy to develop towards miniaturization.
2.2. Wing model
The wing is a rectangular wing with a wingspan of 400mm and a chord length of 100 mm. The wing is mainly composed of carbon fiber beam and skin. The wing skeleton consists of carbon rods and the skin consists of polytetrafluoroethylene film. Piezoelectric piece (PZT) is attached to the root of the wing. The wing model is shown in Fig. 3. The properties and dimensions of finite element simulation materials are shown in Table 1. The weight is 4g. The center of mass of the wing is located at 0.1m in the semi-spanwise direction.

3. PCL parametric structure simulation

3.1. Finite element model

|                  | PZT | Carbon beam | Rib Carbon Rod | Polyester film |
|------------------|-----|-------------|----------------|----------------|
| Elastic Modulus(GPa) | 62  | 150         | 100            | 1.4            |
| Poisson's ratio   | 0.33| 0.33        | 0.40           |                |
| density(g/mm3)    | 7.8 | 1.5         | 1.5            | 1.2            |
Figure 4. Wing shape and size settings window.

PCL module in finite element software Patran is used to simulate the structure of the wing of piezoelectric actuator. The beam adopts beam element, which is suitable for analyzing beam structures from slender to medium thick and short. The element is based on Timoshenko beam structure theory and takes into account the effect of shear deformation of carbon fiber rods. Rib adopts Bar element, and thin film adopts shell element, and PZT piezoelectric sheet adopts shell element, and wing shape definition is shown in fig. 4, grid division is shown in fig. 5.

Figure 5. Meshing.

3.2. Boundary conditions
The wing has only the freedom to rotate about the x-axis. When the nodes on the body coordinate system and the X axis rotate in the inertial coordinate system at the same angular frequency as the wing, the root chord is in a relatively stationary state. The maximum flapping angle of flapping wing is 70, and the flapping frequency is 7.8Hz. The structure has symmetrical flapping up and down, and in a single upper flapping angle or lower flapping angle, the flapping angle above the horizontal line is 45 degrees greater than the flapping angle below the horizontal line is 25 degrees; with passive chordwise torsional deformation.

3.3. Load belastung
Loads on the wing include aerodynamic and inertial forces. The aerodynamic force is decomposed along the wing spanwise and is directly applied to the wing rib. Inertial force is also directly applied to wing ribs in the form of uniform load.

3.3.1. Aerodynamic force. The force on the wing of flapping wing consists of aerodynamic force and inertial force. In the study, the flapping wing model with the same size is set to 10m/s in the incoming
flow velocity and its flapping frequency is 7.8Hz. Under the condition that the angle between the central axis of the fuselage and the incoming flow is 0 degree, wind tunnel experiments were carried out in this study. According to the experimental results, the corresponding relationship between lift, drag and instantaneous flapping angle is shown in fig. 6. Lift force is distributed along spanwise direction. Refer to Figure 4 [12] of the article for specific spanwise distribution.

![Figure 6. Lift and Drag versus instantaneous flapping phase.](image)

3.3.2. Inertia force on wing. When the wing is flapping periodically, the wing will generate periodic inertial force. The calculation formula of inertial force is as follows:

\[ F_{\text{inertial}} = \sum_{i=1}^{n} m_i a_i \]  

Where \( m_i \) is the mass of the i mass element of the wing, and \( a_i \) is the linear acceleration corresponding to the i mass element.

Because the inertial force of the wing is an illusion force that retards the movement of the wing, the larger the inertial force, the greater the input power required to drive the wing to flutter and the more serious the energy consumption. Therefore, the influence of inertial force on wing deformation should be minimized in aircraft design. The maximum positive value of the inertial force of the wing is 0.689N, and the minimum negative value is -0.515 N [12].

3.4. Results and analysis

After finite element simulation, the first-order modal natural frequency of the model is 6.74Hz, as shown in fig. 7. The natural frequency of the second-order mode is 19.39Hz, as shown in fig. 8. The third-order natural frequency is 25.49Hz, as shown in fig. 9. As the frequency of force is close to a certain natural frequency, it may cause structural resonance, and the structure will generate strong vibration, thus realizing high-frequency flapping. The relationship between wing structure and its natural frequency and vibration mode is studied by using finite element analysis method to carry out dynamic analysis on wing structure. This conclusion provides a certain basis for studying the dynamics of wings and improving the design. The flapping frequency of the flapping wing vehicle with piezoelectric actuator is 12Hz, so the simulation results of finite element model are close to the real situation.
4. Development of piezoelectric actuator wings

From the simulation results, this paper developed a flapping wing using piezoelectric actuators. In this experiment, the power amplifier is powered by two channels. The experimental voltage is 160V. When the flutter frequency and the resonance frequency of the wing are the same, the flutter frequency generated by the piezoelectric motor wing is 12Hz, and the maximum deformation of the wing tip of the piezoelectric flapping wing is ± 32mm. The piezoelectric actuator wings are shown in Figure 10, and the piezoelectric actuator flapping wings are shown in Figure 11.

5. Conclusions

In this paper, the finite element model of flapping wing of piezoelectric actuator is established by using PCL language. In this study, cBased on the aerodynamic experimental data of flapping wing with the same size, a dynamic simulation of the piezoelectric actuator flapping wing structure was carried out. Studies have shown that after using piezoelectric actuators, the flapping frequency of flapping wings is significantly increased from 8 Hz to 12 Hz. This conclusion provides a certain basis for studying the wing dynamics and improving the design. With the development of MEMS technology, the quality of power amplifiers, piezoelectric plates and other components will be greatly reduced, which will cause the flutter frequency to increase significantly. According to the results of previous studies, it is helpful to increase thrust when the flutter frequency increases. Since the research shows that the frequency has relatively little influence on the lift, the use of piezoelectric actuators can help improve the aerodynamic efficiency of flapping wings.

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