Experimental Study on the Stiffness and Shape Layout of Flapping Wing

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Abstract. Flapping-wing Micro Air Vehicle (FMAV) is a kind of bionic air vehicle, which looks like natural flying creatures and flies by flapping-wings only. Now, there is an upsurge of relative research about FMAV, and one focus research domain is to develop a flapping-wing with high aerodynamic performance. The wind-tunnel experiment is one of the main research manner, which can be used to test and control many parameters with high accuracy, like force, torque, flapping angle, frequency, power, etc. Based on the wind-tunnel system and inspired by birds, we mainly study the effects of stiffness and shape layout of the flapping wing, and get some conclusions. And this work may set up a good fundamental for further experiment about developing wing with high efficiency.

1. Introduction

The flapping-wing micro air vehicle (FMAV) is a type of aircraft inspired by the flight patterns of natural birds, bats or insects. It generates lift and thrust through the flapping wings to overcome the gravity and drag during flight. Ideally, FMAV can hover or even fly backward, such as dragonfly. It also has the characteristics of fast cruising speed and high aerodynamic efficiency. [1-4]

FMAV is flexible in operation, small in size, light in weight, low in cost, and easy to carry. In the near future, the use of FMAV will certainly become more and more extensive, in social public security work, and in special occasions (such as dangerous or inaccessible), FMAV can play an important role in the information acquisition and delivery work.

As a new type of micro air vehicle, researches on it is developing [5-9]. The mode of flapping wing flight is completely different from that of fixed-wing flight. It involves unsteady aerodynamics with low Reynolds number and many other fields that people have not fully understood. At present, wind tunnel experiment is one of the main research manners. [10,11]

The flapping-wing flight mode of natural creatures can be roughly divided into two modes: low-frequency flight modes like birds and bats, and high-frequency flight modes like insects such as bees and crickets. Future flapping wings are likely to move towards these two modes. In the first flight mode, the bird-like FMAV has a relatively large size and a low flapping frequency. It is suitable for outdoor flight over a long distance. In another flight mode, the insect-like FMAV has a smaller size and a higher flapping frequency. It is suitable for small-scale indoor flight at short range.

The size and flapping frequency in this experiment are similar to birds, so here we only study the flight of birds. By observing the flight of birds, it is known that the wings of birds are generally not straight when flying, but are divided into two sections, inside and outside, and have a certain forward or sweeping angle in the spanwise direction, as shown in Figure 1. There arises some questions: will this layout have some beneficial effects on the aerodynamics or other aspects of the wings? If so, can...
this bring some inspiration to our FMAV? It is for this purpose that we have designed the layout experiment of this paper.

![Birds: Albatross, Swallow, Pheasant, Eagle](image1)

**Figure 1.** The wings of several birds

This paper is arranged as follows: In the section 2, the wind tunnel experimental system is shown, and the process of collecting and processing the experimental data. The steps of the experiment are introduced. In the section 3, the purpose of the experiment is described, and the experimental preparation, the parameters and fabrication of the wing. The experimental equipment configuration and experimental parameters, including wind speed, flutter frequency, angle of attack, and the processing of experimental data and the analysis of experimental results are also discussed. In the section 4, the experimental data are analyzed in detail, including the effects of the stiffness layout and shape layout of the wing on aerodynamics and power consumption.

### 2. Wind tunnel experiment system

#### 2.1. Wind tunnel

The experiment was carried out at the low-turbulence wind tunnel in Northwestern Polytechnical University (NPU), shown in Figure 2(a). The wind tunnel is a DC low-speed wind tunnel, with the test section of $2\times 1.05\times 1.2$ m (length × width × height), which has a steady wind speed range from 5 m/s to 25 m/s, and the turbulence is 0.02%.

![Wind tunnel](image2)

*Figure 2. Low-turbulence wind tunnel in NPU and the flapping mechanism in experiment*

#### 2.2. Force/Torque sensor

The aerodynamic force generated by the flapping wing is relatively small, generally less than several hundred grams, and periodically changes with the flapping of the wing, which determines that the force/torque sensor should have high precision and high sensitivity. The Nano17 multi-axis force/torque sensor of ATI Company is suitable for our experiment.

#### 2.3. Flapping mechanism

A flapping mechanism was specially designed and manufactured to achieve the flapping of the wing, shown in Figure 2(b). The mechanism consists of a four-bar mechanism, a brushless DC motor with a KV value of 6400/v, a diameter of 12 mm, a length of 30 mm, a working speed of 44800-52480 rpm, and a secondary gear reduction with a reduction ratio of $I=60.2$. 
2.4. Measurement and control software
The experiment uses the LabView 8.2 to deal the measurement and control processes. The design of the whole software should include two modules. The measurement module is used to realize the acquisition and processing of experimental data, and the control module is used to realize the flapping control of the mechanism. The control module includes control of the power switch and the frequency.

3. Flapping wing layout experiment
In order to study the influence of different stiffness and shape layouts on aerodynamic forces, seven pairs of contrasting wings were specially fabricated. The main purpose of this paper is to study the influence of the layout. The seven wings are flat with no curvature. The basic shape of the wing is rectangular or parallelogram, and the initial installation angle of the wing is 0°. The wing is mainly composed of a skeleton and a skin, wherein the skeleton is made of carbon fibre rods with different diameters, and a membrane skin is laid on the surface, and the specific shape of the wing is shown in Figure 3. The skeleton of each wing consists of two main beams and six ribs. The wings have a span length of 220 mm and a chord length of 100 mm. The six ribs are evenly arranged along the span, with a spacing of 44 mm, and the ribs of each pair of wings are the same size.

![Figure 3. Experimental wings](image)

The relevant parameters of the seven pairs of wings are shown in Table 1.

| Grouping       | Wing No. | Wing parameters | Remarks                  |
|----------------|----------|----------------|--------------------------|
|                |          | Front beam (mm) | Back beam (mm) | Rib (mm) | The wing is a flat wing |
| First group (stiffness) |          |                |                      |          |                        |
|                | 1        | 2.0            | 1.5                   | 1.0      |                        |
|                | 2        | 2.0            | 1.5                   | 1.5      |                        |
|                | 3        | 1.5            | 1.5                   | 1.0      |                        |
| Second Group (shape) |          |                |                      |          |                        |
|                | 4        | 40%            | -15°                  | +15°     | “-” means forward sweep |
|                | 5        | 40%            | +15°                  | -15°     | “+” means backward sweeping |
|                | 6        | ----           | -15°                  | -15°     |                        |
|                | 7        | ----           | +15°                  | +15°     |                        |

The first three pairs of wings (No.1-3) are the first group to explore the influence of the stiffness layout on the aerodynamic forces. From the previous analysis, the stiffness of the wing is mainly determined by the skeleton, so the stiffness of the wing can be changed by simply changing the diameter of the carbon rod. The advantage of this method is that it only changes the stiffness of the skeleton that makes the results more comparable.

The rear four wings (No.4-7) are the second group used to explore the effects of the wing’s shape layout on aerodynamic forces. In order to ensure that their stiffness keeps the same, the carbon rod parameters of the skeleton are taken as the same as the wing No.1, and the relative positions of the spar and the rib are also kept as similar as the wing No.1. The wing No.4 and No. adopt two parts, and
the segment positions are 40% from the wing root; the inner wing of the wing No.4 is swept forward, and the outer section is swept back, similar to the wing layout of the birds. The wing No. 5 is just the opposite. The inner section is swept back and the outer section is swept forward. The wing No.6 and No. 7 each have a certain forward or sweeping angle. The wing No. 6 is swept forward and the wing No. 7 is swept back.

The experimental wind speed is 6m/s, the flapping frequency is 8Hz, and the experimental angle of attack is taken from -3° to 36° with an interval of 3°.

4. Results and discussion

4.1. Effect of stiffness

The effects of the stiffness layout includes a total of three pairs of wings, No. 1, No. 2, and No. 3. The specific parameters of the three pairs of wings are shown in Table 1. It can be seen that the overall stiffness distribution of the three pairs of wings is approximately the same, but the stiffness is different. The beams of the wing No. 2 are the same as the wing No. 1. The ribs are thicker than the No. 1, so the No. 2 and the No. 1 have similar span stiffness, and the chord wise stiffness is larger than that of the No. 1. The rib of the No. 3 is the same as that of the No. 1, and the beams of the wing is thinner than that of the No. 1, so the chord stiffness of the wing No. 3 and the wing No. 1 is similar, and the span stiffness is smaller than that of the wing No. 1.

Generally speaking, for a rigid flat wing (which is very stiff and can be considered as barely causing structural deformation), when the angle of attack is zero, it cannot produce an effective average aerodynamic lift, but just some thrust. But for flexible wings, it can produce an effective average aerodynamic force including lift and thrust, which is mainly due to the flexible structural deformation. In the process of flexible wing flapping, the aerodynamic force acting on the wing causes the wing to be passively deformed, and this deformation in turn changes the aerodynamic force on the wing. This coupling phenomenon is beneficial in a certain extent. On the one hand it can generate additional effective average aerodynamic forces, on the other hand it can help the wing to unload and protect the structure.

Figures 4 shows the lift coefficient and thrust coefficient as a function of angle of attack for wings No. 1, No. 2 and No. 3.

![Figure 4. Aerodynamic coefficient of wings with different stiffness](image)

(a) Lift coefficient (b) Thrust coefficient

It can be seen from the curves that the lift coefficient of the wing No. 2 is similar to that of the wing No. 1, and the thrust coefficient is larger than that of the wing No. 1; the lift coefficient of the wing No. 3 is smaller than that of the wing No. 1, but the thrust coefficient is bigger than the wing No. 1. Therefore, the chord wise stiffness has no significant influence on the lift force, and the impact of stiffness is greater on the lift force, and within a certain range, the lift stiffness is larger when the span wise stiffness is larger. For the thrust, the change in stiffness seems to be more sensitive, both the span wise stiffness and the chord wise stiffness have an obvious effect on it. The general trend is that the thrust is larger when the chord wise stiffness is larger.
4.2. Effect of shape layout

In the design of the FMAV, the shape of the wing directly determines the performance of the entire aircraft, which shows the importance of the shape layout of the wing. In fact, the shape selection of the flapping wing is crucial. A good shape can produce large aerodynamic force, but a bad wing shape may be counterproductive, making the aircraft performance reduced. As mentioned earlier, the wings of birds are always divided into two sections, then what is the advantage of this shape layout? Is it possible to generate a large effective aerodynamic force? To this end, we carried out a second set of experiments, which mainly consisted of four pairs of wings from No. 4 to No. 7. The specific parameters of the four pairs of wings are shown in Table 1. Generally speaking, the wing No. 4 is a bird-like layout. The inner section is swept forward and the outer section is swept backward; the wing No. 5 is just opposite, the inner section is swept backward and the outer section is swept forward; the wing No. 6 is swept forward; the 7th wing is swept backward.

According to the existing information, the inner and outer sections of the wing bear different “responsibility”. The inner section mainly produces lift, and the outer section mainly generates thrust. The existing wing design method basically relies on this principle to achieve the requirements of large thrust and high lift. Figures 5 shows a comparison of the lift and thrust coefficients for the No. 1 and No. 4 to No. 7 wings, respectively.

![Lift coefficient](image1)

![Thrust coefficient](image2)

**Figure 5.** Aerodynamic coefficient of wings with different shapes

It can be seen from the curve in Figure 5(a) that the lift coefficient of the wing No. 6 is the largest, followed by the wing No. 5, and the wing No. 7 is the smallest. Therefore, in terms of lift generation, the forward swept wing is the best choice, the backward swept wing is the worst, and the wing No. 4, which imitates bird mostly, does not get the high lift we expected. But instead it is opposite to the shape of the wing No. 4, the wing No. 5 is capable of generating greater lift.

Referring again to Figure 5(b), the thrust coefficient curves of the respective wings generally show the following relationship: the wing No. 7 is the largest, the wing No. 5 and the wing No. 6 are equivalent, occupying the second position, and wing No. 1 is the smallest. That is, the swept wing produces the most thrust, and the imitation wing No. 4 does not produce the large thrust as we would expect.

From the above analysis, the lift and thrust generated by the Wing No. 4 is not the biggest, that is, its aerodynamic characteristics are not good; while the No. 6 forward swept wing produces the largest lift and the thrust is relatively large. The comprehensive aerodynamic characteristics are the best.

5. Conclusions

The experiment explored the aerodynamic characteristics of the flapping wing. The effects of the stiffness layout and shape layout on the aerodynamic parameters are studied. The experimental results are helpful to understand the law of flapping flight in some extent.

In order to study the effects of stiffness layout and shape layout, seven pairs of wings were made and divided into two groups. The first group consists of three pairs of wings, each of which has different stiffness; the second group consists of four wings, each of which has a different shape. Through two sets of comparative experiments, the following can be concluded:
The aerodynamic force of the flapping wing has a great relationship with the stiffness, and the flexible deformation of the flapping wing enables it to produce an effective average lift and thrust. For lift, the chord stiffness has little effect on it, and the span stiffness has a great influence on it. Within a certain range, the lift increases as the span stiffness increases. For thrust, stiffness has a greater impact on it, and its magnitude is related to both the span and the chord stiffness. When the span stiffness is small and the chord stiffness is large, the thrust is large. The effect of the chordwise stiffness on the thrust is greater than the span stiffness.

By comparing the experimental data of the four wings No.4 to No.7, it can be found that the wing No.6 with forward swept shows best aerodynamic performance. Therefore, when the wing takes a certain forward sweep angle, it is advantageous for the aerodynamic characteristics and overall performance of the wing.

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