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Wing shape optimization design inspired by beetle hindwings in wind tunnel experiments

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1. Introduction

Due to unsteady aerodynamic effects, flapping wings may be a more energy-efficient flight mode than modes achieved with traditional fixed and rotor wings [1–4]. As our ultimate goal, deployable flapping wing microair vehicles (DFWMAVs) will make microair vehicles (MAVs) smaller in size, lighter and more camouflaged. Coleoptera, popularly referred to as beetles, are regarded as an interesting bionic prototype for MAV miniaturization [5]. In contrast to those of other flying insects, the flight wings of some beetles are deployable and can fold automatically between the elytra and the abdomen by a self-locking friction mechanism [6]. The morphology, structure and folding mechanism of the hindwings of different beetles vary significantly according to their living environment. Therefore, the design of DFWMAVs may be improved by research on deployable beetle hindwings [7].

We can learn from flies [8,9], dragonflies [10,11], beetles [12], butterflies [13,14], hawkmoths [15], etc. Their wings have multiple degrees of freedom and can quickly switch from one flight mode to another by adjusting the wing motion patterns and wing geometry [16]. In the 3D numerical study of insect wings, the leading edge vortices (LEVs) on these flexible wings have been found to be stronger and more stable; the mean lift coefficient of a highly flexible wing surpasses that of a rigid wing at \text{AOA} > 30\degree [17]. In research on the wing inertia of a flexible flapping wing, the aerodynamic performance of the fluid force-dominated wing flexibility is larger than that of the inertial force-dominated wing flexibility [18]. In research on the forward flight of flexible wings, passive pitching due to flexible wing deformation can significantly increase thrust [19]. Some researchers also found that both the phase and the rate of passive pitching due to wing flexibility can significantly improve the aerodynamic performance of the wing [20]. In a study of fruit fly wings, the chordwise flexibility of flapping wings may passively stabilize hovering insects [21]. Therefore, the internal mechanism between flexibility and flight dynamics was revealed in these studies.

In previous research on insects and MAV wings, some important shape parameters were discussed. In a study of insect wings, some researchers predicted the optimal aspect ratio (AR) = 3 based on the mean lift coefficient of the wing, because the increase in the LEV cross-sectional size along the span causes the LEV to reach the trailing edge (TE) without reattaching and then weakens through the influence of the opposite sign vorticity from the TE for AR > 3 [22]. Wings with a low radius of the first moment of the wing area (r\text{\textsubscript{1}} = 0.43) and high AR (AR = 2.96) are best for maximizing the power efficiency of insects for a given lift [23]. Regarding the effect of the flexibility of insect wings on different mass ratios (m*) and ARs, a higher power efficiency (increase of 33%) was obtained at AR = 6.0 and m* = 0.66 [24]. In some studies of MAV wings, regarding the effect of the AR on the LEV in the study of a rigid rectangular wing, the highest lift coefficient was produced when

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AR = 12 [25]. In the simulation of flapping wings in forward flight, the camber line, LE and TE were confirmed to be the key wing shape parameters that control the generation of aerodynamic loads and flight performance [26]. In the wing rotation study, wing flapping with a high AR performed better at large angles of attack (>20°) and performed best with AR = 8 [27]. In a shape optimization study of flapping wings, an evolutionary structural optimization method was adapted as the Reynolds number was varied, and these optimized shape wings have higher lift coefficients (~50%) than the initial rectangular wing [28]. Some studies have explained that the camber angle and AR have a significant influence on aerodynamic force generation [29]. In a water tunnel experiment, the wing span and chord flexibility were beneficial to the aerodynamic performance with different Reynolds numbers and flapping frequencies [30,31]. However, existing artificial flapping wing microair vehicles (FWMAVs) [12,32–35] simply mimic the curves of biological wing profiles or transform simple geometric shapes. The wing shape parameters, especially the wing membrane, are less optimized. Therefore, it is important to research the optimal wing geometry for achieving high lift.

To optimize the wing shapes of DFWMVs, three species of beetles living in different environments, including Cybister japonicus Sharp (in which live in water), Copris ochus Motschulsky (in which live in soil), and Harmonia axyridis (in which live in woods), were selected in this paper. Based on the geometrized features of the hindwings of the three species, the wing profiles were simplified into rectangles, right-angled trapezoids, and pentagons. The red line indicates the position of the fold line. The solid line is a chord, and the dotted line is spanwise. C, costa; ScA, subcosta anterior; MP, media posterior; CuA, cubitus anterior; AP, anal posterior; SV, supporting vein.

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beetles, bioinspired wings with various parameters were designed. Wings were fabricated and tested in a low-speed wind tunnel to optimize the maximum lift together with the efficiency. The results of this work will be helpful in the design of DFWMAVs.

2. Materials and methods

2.1. Specimens

Coleoptera, also referred to as beetles, have two pairs of wings: forewings (elytra) and hindwings. The elytron is stiff (blister beetle, which have softer elytra, are the exception [36]), and it completely or partially (such as for the rove beetle [37]) covers the abdomen. These wings have characteristics such as low weight, high strength, super-hydrophobicity, color changes and anti-adhesion [38,39]. The hindwing is soft, and the microtrichia that attach to its surface have many functions [40], such as producing stridulations, increasing friction, creating a buffer to protect the body from damage, sensing the surrounding environment and interlocking [6].

Given the different living environments and conditions of different beetles, there are distinct variations in the shape, vein structure and folding mechanism of the hindwing [7]. Therefore, we chose flying beetles, there are distinct variations in the shape, vein structure and folding mechanism of the hindwing [7]. Therefore, we chose flying beetles living in different environments (land, soil and water) for this study: Harmonia axyridis, Copris ochus Motschulsky and Cybister japonicus Sharp (Fig. 1A, B and 1C). H. axyridis was captured from Changchun, Jilin Province. These beetles usually live in thick woods and prefer flying; the adult body length ranges from 6.05 to 7.14 mm, and the length of a single wing is 7.74 mm. Copris ochus Motschulsky were captured from Jilin, Jilin Province. They generally live in the soil. Because this beetle can remove biological excrement, it is considered a dung beetle. The adult body length ranges from 25.13 to 27.42 mm, and the length of a single wing is 35.39 mm. Cybister japonicus Sharp were captured from Guangzhou, Guangdong Province. They usually live in rivers or ponds and can fly after leaving the water. The adult body length ranges from 35.33 to 41.16 mm, and the length of a single wing is 21.48 mm.

In the folding ratio (FR) of the hindwing, which is expressed as ML/WL (WL, total wing length; ML, length of apical membrane), varies. The FRs of the three beetles are 0.58, 0.48 and 0.41. In addition, in the folding shape, Harmonia axyridis has a “Z” pattern. The other two hindwings have a “V” pattern.

2.2. Geometric model

The hindwings of the three beetles were removed from their bodies by tweezers. The morphologies of the veins, fold lines and fold shapes were observed by a 3D microscope system (VHX-6000, Keyence, Japan), as shown in Fig. 1. The profile of the hindwing can gradually be simplified into a rectangle, right-angled trapezoid and right-angled pentagon. The pentagon shape was chosen as the starting point of this research. As shown in Fig. 2A, a geometric model was established. The LE is designated a. The TE is designated c. The CA and CT represent the chord length of the wing root and the chord length of the wing tip, respectively, and their lengths were designated b1 and b2, respectively. a is the camber angle, and β is the taper angle (TR).

2.3. Theoretical estimation of flapping aerodynamic force

According to classical steady flow theory, the influence of wing geometry parameters on average lift can be roughly estimated [41]. First, the following lift coefficient equation can be obtained by solving the Navier-Stokes (N-S) equation:

\[ C_L = \frac{2L}{\rho v^2 S} \]  

where \( C_L \) is the lift coefficient, \( L \) is the lift generated by flapping, \( \rho \) is the air density, \( v \) is the average velocity relative to air, and \( S \) is the whole wing area.

As shown in Fig. 2A, the wing can be divided into \( n \) rectangular strips by the calculus method, so the area of each small strip is \( da \times h(b) \). When the wing is divided into many segments, the width of each segment is very small, and the flow is constant. The aerodynamic coefficients on each wing segment can be approximately considered to be similar. The transient lift can be obtained after improvement:

\[ F_L = \frac{1}{2} \int_0^a C_L \rho \left( a \frac{d^2(b)}{dt^2} \right)^2 h(b) da \]  

Therefore, the average lift can be expressed as:

\[ F_L = \frac{1}{T} \int_0^T F_L dt \]  

where \( F_L \) is the transient lift, \( a \) is the single wing length, \( \theta(t) \) is the angular displacement, \( h(b) \) is the length of each segment, and \( T \) is one flapping cycle.

If we accept the quasi-steady assumption, then the approximate solution of the average lift is:

\[ F_L = \frac{1}{2} \rho L_c (2S_w)^2 \]  

In this equation, \( \rho \) and \( v \) are constant. The main factors affecting the average lift are \( C_L \) and single wing area \( S_w \). Therefore, the geometry of the wing determines \( C_L \). The center of the wing aerodynamic pressure is assumed to be located at the center of a single wing length [12]; then, \( a_0 = \frac{1}{2} a \). If the flapping frequency and amplitude of a flapping wing system are \( f \) and \( \phi \), respectively, then the average velocity \( v \) can be expressed as:

\[ v = 2f a_0 \phi = \frac{1}{2} \phi fa \]  

In addition, according to the geometric characteristics of the wing, the equation of the single wing area \( (S_w) \), AR, TR and slope \( (\tan \beta) \) can be expressed as:

\[ S_w = \frac{b_1(a + c) + b_2(a - c)}{2} \]  

\[ \text{AR} = \frac{4a}{3b_1 + b_2} \]  

\[ \text{TR} = \frac{b_2}{b_1} \]  

\[ \tan \beta = \frac{b_1 - b_2}{a - c} \]  

Combined with (4) and (5) and (7), the cycle average lift of a pair of wings can be expressed as:

\[ F_L = \rho L_c S_w (\phi fa)^2 \]  

Therefore, equation (10) shows that the average lift should be approximately linear with \( C_L \) and the wing area but quadratic with the flapping amplitude and flapping frequency.

2.4. Flapping mechanism

The flapping wing mechanism is shown in Fig. 2B, which was designed in our previous research [42]. This mechanism, which will be employed for all the experiments in this research, was composed of a double crank linkage mechanism. The linkage mechanism was driven by a brushless direct current (DC) motor, which was used to transform the motor shaft rotation into the flapping motions of the wings. The frame
and wing TE fixing frame were connected by square holes. The arc design of the frame head increases the stability of the whole device and reduces self-vibration. A series of small holes in the wing TE fixing frame facilitate adjustment of the position of the wing TE. A two-stage gearbox (reduction 1:14.22) was selected to reduce the motor speed. The motor gear was engaged only with the crank gear on the left. The right crank gear was driven and led by the left crank gear. All the revolute pairs were connected by a pin shaft, which directly transformed the rotating motion of the crank into the flapping motion of the output link.

The flapping mechanism prototype is shown in Fig. 2C. The frame, TE fixing frame and links were all 3D printed. A gearbox with injection-molded gears was utilized. The rivets at each position were made of

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<td>41.67</td>
<td>16.67</td>
<td>37.5</td>
<td>7.06</td>
<td></td>
<td>4115</td>
<td></td>
</tr>
<tr>
<td>W5</td>
<td>130</td>
<td>43.33</td>
<td>17.33</td>
<td>39</td>
<td>7.06</td>
<td></td>
<td>4450</td>
<td></td>
</tr>
<tr>
<td>W6</td>
<td>135</td>
<td>45</td>
<td>18</td>
<td>40.5</td>
<td>7.06</td>
<td></td>
<td>4800</td>
<td></td>
</tr>
<tr>
<td>W7</td>
<td>140</td>
<td>46.67</td>
<td>18.67</td>
<td>42</td>
<td>7.06</td>
<td></td>
<td>5161</td>
<td></td>
</tr>
</tbody>
</table>
stainless steel 304, which was used to connect linkages. The brushless DC motor (Faulhaber, 0620, Germany) weighed 2.5 g, and the revolution constant was 3000 rpm/V, which was placed in the frame center. Wing bars at the leading edge (LE) were made of carbon fiber-reinforced polymer (CFRP) rods with a diameter of 0.8. The flapping frequency was approximately 45 Hz without any wing parts, and the mechanism weighed 5.93 g without a motor. The starting torque was very small, and a voltage of only 0.1 V was needed to normally start the motor. The resulting optimal flapping parameters were obtained by a series of wind tunnel tests: the flapping frequency was 10 Hz; the flight speed was 2 m/s; the angle of attack was 25°; and the mechanism became cambered and twisted after assembly, as shown in Fig. 2D. The wing with different parameters was designed by AutoCAD software and processed through a laser marking machine, which greatly improved the efficiency of machining. Only 2 min was needed to make a pair of wings.

2.5. Wing geometry parameters

To obtain the optimal wing design of this flapping mechanism, maximum lift must be produced. We set the wing length \(a\), camber angle \(\alpha\), AR, TR and \(s_0\) as the geometric parameters of the wing. The camber angle was defined as the angle between the wing root edge and a normal to the LE (refer to Fig. 2A). This parameter describes the curved angle of an airfoil, which will affect the aerodynamic distribution of the whole wing. The whole wing planform shape was a pentagon with two right angles. These two right angles were located at the wing root, and the chord length of wing root \(C_R\) was always larger than that of wing tip chord \(C_T\).

A BW model, as shown in Fig. 2E, was set as the starting point of the wing design. It was the basic wing for the entire study. To understand the influence of each wing parameter, the method of controlling variables was adopted, and only one parameter was changed at a time. A total of 5 wing series were manufactured and tested. The parameter list of the wing geometric design is shown in Table 1. First, the influence of the camber angle was investigated (Group 1). The optimal camber angle that was obtained was applied in the tests of the remaining groups. The wing area of groups 2–4 was constant. The variable parameter of Group 2 was the TR, which was changed by increasing/decreasing the chord length at the wing root/tip. The AR was fixed to the minimum. In Group 3, the variable parameter was the AR, and the TR was the same as the TR in the BW model. In addition, TEs of different lengths were designed: 24 mm, 36 mm, 48 mm and 72 mm. Therefore, Group 3 was divided into 4 subgroups. In Group 4, the AR and TR were changed simultaneously. To keep \(S\) constant, the wing root chord \(C_R\) was fixed, and the TR decreased with an increase in AR. Similar to Group 3, 4 subgroups with different TEs were established. In Group 5, the AR and TR were set to the optimum values determined by previous experiments. The effect of wing area was investigated.

2.6. Fabrication of wing

The wing was inspired by the geometric model of the beetle hindwing. The components of the wing assembly included CFRP wing bars and the wing. The Tyvek membrane (thickness 25 \(\mu\)m) was chosen as the wing planform material, as shown in Fig. 2D. The material is thicker than polyethylene (PE), polyvinyl chloride (PVC), polyester film (polyethylene terephthalate, PETP) and polyimide (PI). However, the weight of a single wing does not differ much, and the difference is only 39 mg, as shown in Table 2. In addition, the Tyvek membrane has many advantages, including strong toughness, tear resistance, water resistance, anti fouling and weatherability. These advantages are helpful for the mass production of wings.

At the LE of the wing, a sleeve was designed. First, the CFRP wing bar was encircled by the LE sleeve. The assembly was completed by bolting the TE hole (as shown by the red arrow in Fig. 2C) to the wing TE frame. In addition, the sleeves can rotate freely around the bars. Near the body, the sleeve and bar were pasted with tape, which prevented the connection from being too loose. Therefore, the stability of the LE and TE of the wing was guaranteed. Since the angle between the LE and inner edge of the wing was greater than 90°, the wing became cambered and twisted after assembly, as shown in Fig. 2D. The wing with different parameters was designed by AutoCAD software and processed through a laser marking machine, which greatly improved the efficiency of machining. Only 2 min was needed to make a pair of wings.

2.7. Wind tunnel

The tunnel test was performed at a low-speed straight-flow wind tunnel at Jilin University, China. The main parameters of the wind tunnel are shown in Table 3. The model was fixed on the bracket, which was connected with the force balance (load cell) after adjustment. The selected load cell (LH-SZ-02, Shanghai Liheng, China) has the advantages of small size, high precision and fast response and is suitable for flapping wing experiments.

After each wing was installed on the flapping mechanism, the wind speed was adjusted to 2 m/s; the flapping angle was 45° and the attack angle was 25°. These parameters comprised the optimal combination of the flapping mechanism in our previous research [42]. The change in average lift with time was tested under different flapping frequencies (set to 0–12 Hz, with an interval of 2 Hz). The motor voltage was 2.5 V at the highest flapping frequency of 12 Hz. The motor can continue to run at higher voltage, but the performance weakened slowly due to temperature rise and brush wear after a period of testing. The measurement of each wing was carried out three times, and each flapping time was 10 s. Since wings of different geometric shapes produce different aerodynamic loads during flapping, the voltage value corresponding to the flapping frequency varies with a change in wings. Therefore, the voltage values corresponding to the flapping frequency were measured by a high-speed camera, which ensures the accuracy of the results.

Table 2

<table>
<thead>
<tr>
<th>Wing material</th>
<th>Density (g/cm³)</th>
<th>Elastic modulus (GPa)</th>
<th>Thickness (μm)</th>
<th>Single wing mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>910–925</td>
<td>7–24</td>
<td>15</td>
<td>0.058</td>
</tr>
<tr>
<td>PVC</td>
<td>1300–1580</td>
<td>45–50</td>
<td>12</td>
<td>0.053</td>
</tr>
<tr>
<td>PETP</td>
<td>1370–1380</td>
<td>57</td>
<td>15</td>
<td>0.068</td>
</tr>
<tr>
<td>PI</td>
<td>1340–1600</td>
<td>80–100</td>
<td>18</td>
<td>0.069</td>
</tr>
<tr>
<td>Tyvek</td>
<td>200–1200</td>
<td>60</td>
<td>25</td>
<td>0.092</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Test section parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working section shape</td>
<td>Rectangle</td>
</tr>
<tr>
<td>Working section area (mm²)</td>
<td>650 × 450</td>
</tr>
<tr>
<td>Length of working section (mm)</td>
<td>1000</td>
</tr>
<tr>
<td>Turbulent intensity (%)</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>Regulator form of wind speed</td>
<td>Hot wire sensor</td>
</tr>
<tr>
<td>Range of wind speed (m/s)</td>
<td>0–10</td>
</tr>
<tr>
<td>Airflow nonuniformity of working section (%)</td>
<td>&lt;3</td>
</tr>
</tbody>
</table>
confirmed that the wing with a small camber angle remained almost flat. With an increase in camber angle, the wing surface begins bending in the chord direction and twisting in the span direction. These changes contribute to the increase in lift coefficient. However, with a further increase in the camber angle, the wing is too flexible, and the effective angle of attack decreases gradually due to excessive curvature, so the average lift begins to decrease. By adding elastic material to the wing root of a bioinspired insect wing, some researchers have also effectively enhanced the lift [45]. The elastic material bends upward, producing the root of a bioinspired insect wing, some researchers have also effectively contributed to the increase in lift coefficient. However, with a further angle of attack, and bends inward, producing the camber angle. The average lift begins to decrease. Based on this analysis, the 10° camber is optimal and will be utilized for the wings in the following sections.

3.2. Effect of taper ratio

In this section, the influence of TR on the aerodynamic performance of the wing is mainly discussed for the condition of keeping the wing surface S and AR constant. The wing length and AR (a = 110 mm and AR = 6.03) were chosen based on the BW model. The TR was changed by increasing the C_{R}, which varied from 40 mm to 48 mm, while C_{P} was varied from 26 mm to 2 mm, and the TR was varied from 0.65 to 0.04 (Group 2). In addition, to keep the AR constant, the TE value gradually increases with an increase in C_{R}, changing from 24 mm to 45.6 mm. The test results are shown in Fig. 3 C. The average lift is confirmed to increase and then decrease as the TR decreases at the same flapping frequency, mainly because the decrease in the TR increases the wing area at the root, the chordwise lift coefficient increases, and the angle of attack also increases [48]. However, as the TR continues to increase, the C_{P} length drops sharply, and the wing develops toward the tapered wing. The LEV generated by flapping may not be maintained continuously, and flow separation occurs in most areas of the wing surface [49]. Therefore, the average lift starts to drop. With different flapping wing frequencies, some interesting rules were obtained: at low frequencies (<6 Hz), the average lift reaches a maximum value when TR is approximately 0.32, and when the frequency continues to increase (>8 Hz), the average lift reaches a maximum value with TR near 0.48, showing that high-frequency wings prefer a relatively high TR, while a small TR is suitable for lower frequencies. At low flapping frequencies, the wing root area for a low TR is larger, but the wing tip area is small.
During the process of lift generation, the chord flow is the main factor. However, at a high flapping frequency, the wing with a large TR has a low TR, and the transition in the spanwise direction is smooth. During the process of lift generation, spanwise flow is the main factor. In addition, a similar situation was observed in the research process of the FWMAV wing of a bionic hummingbird [29]. The test results of efficiency are shown in Fig. 3D. It shows that the whole efficiency of wing is decreased with increasing frequency, but the different TR have almost consistent descending slope (besides TR = 0.65). When the frequency is less than 6 Hz, the efficiency reaches maximum value at TR = 0.48 and 0.32; and when the frequency is more than 8 Hz, the efficiency reaches maximum value at TR = 0.48, which is a bit higher than TR = 0.32. Therefore, according to the above analysis, the efficiency of wing is the maximum when the TR is between 0.32 and 0.48, and the maximum lift produced with the TR of 0.48 is 12.02 g, and the $\beta$ angle is 16.4°.

3.3. Effect of aspect ratio

Based on the size of the BW model, the effect of AR on the wing by regularly changing the length of $L$ and TE was investigated. With TR unchanged, the wing length changed from 110 mm to 140 mm. The length of TE was set to four groups: 24 mm, 36 mm, 48 mm and 72 mm (Group 3). Therefore, the AR varied from 6.03 to 10.36. The specific parameters are shown in Table 2. The test results are shown in the four graphs in Fig. 4. The change trend of the average lift is consistent at the same frequency. Although the values of TE are different, the AR values of the highest average lift of each group are approximately 7.06. However, with different TE values, the highest average lift produced by each group is 12.07 g, 15.31 g, 13.77 g and 9.08 g. When the TE value is 36 mm, the highest average lift can be reached, which showed that a smaller TE value will cause a lower lift at the trailing edge and an excessively large TE value will cause the LEV of the wing tip to fall off early. High lift associated with the LEV is predominantly spread in the distal region (away from the wing root) and leeward region (toward the TE) of high flapping velocities [23]. A suitable TE value is a necessary condition for obtaining high lift. Therefore, when the AR is 7.06 and the TE value is 36 mm, the wing has the best performance in this group.

3.4. Effect of wings with varying aspect ratio and taper ratio

The effect of TR is related to AR. After discussing the effects of two single factors in Sections 3.2 and 3.3, this situation of two simultaneous factor changes is discussed. In this section, to ensure that the TR and AR change simultaneously, $C_R$ was constant, with a value of 40 mm (equal to BW model). The wing length $a$ was varied from 110 mm to 140 mm, while $C_T$ was decreased from 26 mm to 0.8 mm. The calculated $C_T$ length is too small when the TE is equal to 72 mm. Therefore, this group tests only the lift generated when the TE values are 24 mm, 36 mm and 48 mm. The AR varied from 6.03 to 9.27, and TR varied from 0.65 to 0.02. The specific parameters are shown in Table 2. The test results in Fig. 5 (A, B and C) show that the average lift of each group increases and then decreases when the flapping frequency is constant. Moreover, the AR values corresponding to the peak lift of each subgroup are approximately 7.06. These results show that when the AR and TR are changed simultaneously, the best AR value is the same as the AR of Group 3, and there is no benefit in increasing AR beyond 7.06. Thus, the value of 7.06 was identified as the most efficient in this group. In addition, it was also
found that in insects such as fruit flies, ladybirds and dragonflies, the AR values of the hindwings were lower than this value (AR = 3.0–5.45) [50]. The size and mass of an artificial flying robot are larger than the size and mass of an insect, and the lift can be increased by increasing the AR in a certain range. However, with different TE values, the TR corresponding to the best AR is 0.47, 0.40 and 0.3. The three graphs show that the average lift produced is the largest when \( c = 36 \text{ mm} \), showing that \( c = 36 \text{ mm} \) is the most efficient in this group. In addition, as the TE increases, the TR gradually decreases. The optimal TR value is 0.40, which is 11.1% lower than the best TR value in Group 2, but the average lift is increased by 20.5%, which is significant.

3.5. Effect of surface wing area

Based on the previous discussion of the four series, we observed that the highest average lift value is 23.10 g when \( L = 120 \text{ mm}, \ AR = 7.06, \ TR = 0.4 \) and \( c = 36 \text{ mm} \). The effect of wing surface area on aerodynamic performance was investigated. The optimal parameters that we determined were set as the starting point. Specifically, the wing length \( a \) was ranged from 110 mm to 140 mm, and the wing area \( S \) was varied from 3186 mm\(^2\) to 5161 mm\(^2\) (Group 5). According to the analysis of flapping wing theory in Section 2.3, we conclude that the average lift is positively correlated with the wing area. The test results in Fig. 5D confirms this theory. At the same flapping frequency, the slope of the average lift curve increases and then decreases, and the highest growth rate is near 4115 mm\(^2\). (E) The whole efficiency of wing is decreased with increasing frequency. When the \( f < 8 \text{ Hz} \), the efficiency reaches maximum value at \( S = 4415 \text{ mm}^2 \); and when the \( f > 8 \text{ Hz} \), the efficiency is not obvious better.
possible only at low frequencies. Finally, we chose the wing with a wing area of 4115 mm$^2$. Although the lift is not the highest, but the efficiency of wing is ideal. We also prefer a smaller wingspan due to load, and a more compact design is encouraged.

3.6. Response surface optimization of wing geometric parameters

To fully analyze the influence of wing geometry parameters ($a$, $b_1$, $b_2$ and $c$) on the average lift, based on the wind tunnel test, the design optimization was completed by Workbench response surface optimization simulation. The designed input parameters are shown in Table 4. The output parameter is the average lift force, expressed by code P6 (g). The final simulation results are shown in Fig. 6. The response surface shows the effect of the combination of any two of the four input parameters on the output parameters. Fig. 6A shows that the average lift is positively correlated with the LE length (P2) and the wing root chord length (P3), and the rising rate of P2 is relatively large. From Fig. 6 (B and D), the average lift is positively correlated with P2 and P3 but negatively correlated with the wingtip chord length (P4), and a decreasing rate of P4 is relatively large. Fig. 6C shows that when the TE length (P5) is approximately 36 mm, the average lift reaches the peak, which is consistent with the results of the wind tunnel test. When P5 is less than 36 mm, the average lift is positively correlated with P5, while when P5 is greater than 36 mm, the average lift is negatively correlated with P5. After referring to Fig. 6C and E shows that although the Y-axis is also P5 and the X-axis is P2 and P3, respectively, the average lift in Fig. 6E decreases gradually with an increase in P5, and no wavy shape is observed, as shown in Fig. 6C, indicating that the positive benefit of P2 to P5 is greater than the positive benefit of P3 to P5. The final Fig. 6F shows that the average lift is negatively correlated with P4 and P5, and the rate of decrease of P4 is relatively larger.

To better understand the influence of the input parameters on the output parameters, the local sensitive graphs obtained are described as follows: From Fig. 7, for the average lift (P6) of the model, the LE length

Table 4

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>LE (P2)/mm</th>
<th>The root chord length (P3)/mm</th>
<th>The wing tip chord length (P4)/mm</th>
<th>TE (P5)/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value range</td>
<td>[110, 140]</td>
<td>[3,5]</td>
<td>[3,5]</td>
<td>[24,72]</td>
</tr>
</tbody>
</table>

Fig. 6. Diagram of the response plane of the input parameters to average lift. The designed input parameters are $a$, $b_1$, $b_2$ and $c$, which are represented by P2, P3, P4 and P5, respectively.

Fig. 7. Local sensitive graphs of response surface optimization. For the average lift (P6) of the model, the LE length (P2) has the greatest influence, followed by the root chord length (P3), TE length (P5), and wing tip chord length (P4), which has the smallest influence.
P2 has the greatest influence, followed by the root chord length (P3), the TE length (P5), and the wing tip chord length (P4), which has the smallest influence. These results are consistent with the results of the response surface optimization shown in Fig. 6.

4. Conclusions

The main contribution of this effort was to optimize the wing shape parameters of DFWMAVs by wind tunnel experiments. In this study, the hindwings of three beetles, Cybisler japonicus Sharp, Copris ochus Mot-schulsky, and Harmonia axyridis, were selected. Based on the geometrized features of the hindwings of the three beetle species, a bioinspired geometric model (pentagonal wing) was established. Wings with various parameters were fabricated and tested in a low-speed wind tunnel; the camber angle, wing length, chord length, AR, TR and S were set as the input parameters, the average lift and efficiency of wing were set as the output parameter. The results showed that the camber angle initially had a large impact on lift generation. Compared with TR, AR had a more important effect on lift generation. Moreover, the change in TE length also affected the aerodynamic force. The best performance was obtained by a wing with a camber angle of 10\(^\circ\), wing length of 125 mm, AR of 7.06, TR of 0.4, TE length of 36 mm and single wing area of 4115 mm\(^2\). The ranking of the influences of the wing geometry parameters on the average lift was obtained by response surface optimization. The influence level from high to low was LE length (P2), root chord length (P3), TE length (P5) and wing tip chord length (P4). In future research, more qualitative investigations (via particle image velocimetry (PIV)), especially those on how to improve the flow structures in the flapping wing system, will be carried out to solve the unsteady aerodynamic problem of the flexible wing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Wing shape optimization design inspired by beetle hindwings in wind tunnel experiments”.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.combiomed.2021.104642.

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