1 Introduction

Recently, micro air vehicles (MAVs), which can be applied in both civil and military applications such as search and rescue and reconnaissance, have been intensively researched and developed by many research groups around the world. Most of the work is adopted either principle of bird flight [1-4] or insect flight [5-7], however, most successful flapping-wing MAVs adopt principle of bird flight with a control surface at tail. In contrast, flying insects without tail have many fascinating features of flight characteristics and maneuverable abilities, especially; insects successfully control their flight and attitude using only their flapping wings. Therefore, research efforts have been focusing on mimicking insect flight at desired scale as the next generation of flapping-wing MAVs [8-12]. Despite of much progress in understanding flight principles of both bird flight and insect flight, building a real flapping-wing MAV mimicking birds or flying insect without tail fins is another story and still a challenging task.

The wing is vital for all flying insects. Insect wings are membranous and fragile; however, they are still strong enough to endure the aerodynamic forces produced by flapping wing motion. During flapping flight, wings passively bend and twist resulting in instantaneous changes in aerodynamics due to the coupling effect between wing shape and fluid forces. In addition, the wing flexible has been proven to increase lift by changing fluid directions [13], and flexible wing can delay stall at higher angles of attack [14]. Therefore, biomimetic wings may have advantages for flapping-wing MAVs. In nature, insect wings vary widely in terms of wing shape, vein structure, and cross-sectional; however, there is still no appropriate method for evaluating the wing function and wing morphology.

Despite of these facts that 25% of life-forms in the animal kingdom and about 40% of insects are beetles, approximately 350,000 known species of beetles worldwide, it is more surprising to see that not many features on beetles have been explored. It is quite recent years that beetles draw researcher’s attention [15-18]. Among many beetles, Rhinoceros beetle, Allomyrina Dichotoma, is one of the largest beetles, and thus has relatively high capability of external load carriage. In addition, the large size utilizes the ease of observing and mimicking a real beetle wing at a similar scale.

This work introduces a simple and low cost method of composite fabrication capable of making centimeter-scale biomimetic artificial wings in terms of lightweight, complex venation pattern inspired by the beetle hind-wing, Allomyrina Dichotoma. The method permits customizable variations in wing shape, venation structure, and mechanical stiffness. By this process, a wing can be fabricated with a large range of desired mechanical and geometric characteristics. Static tests for stiffness measurement and dynamic vibration tests for resonant response have been conducted on both real beetle hind-wing and biomimetic artificial wing to compare the stiffnesses and resonant frequencies of the both real beetle hind-wing and biomimetic artificial wings and the similarities of the two wings are discussed.

2 Fabrication of biomimetic artificial wing

The artificial wings mimicking beetle’s hind-wing were made with venation patterns derived from a real beetle [8], Allomyrina Dichotoma. Because we want to simply the wing making process, flat wings without camber were fabricated, and complex structures (such as cellular venation pattern in
dragon fly’s wing) were neglected; we only kept the main venation pattern as shown in Fig. 1, and all veins within a wing were made to uniform width. In the viewpoint of biomimetics, a biomimetic artificial wing must be lightweight, but stiff enough to sustain wing load; thus, it requires a flexible membrane reinforced by a framework of stiff, lightweight veins.

To reduce the wing mass and keep the wing stiffness, we used light weight and high strength materials such as carbon prepreg with 0.1 mm thick, and thin Kapton film used as the membrane of the wing with a uniform thickness of 7.7 µm. The artificial wings were carefully made by hand to maintain the identical characteristics for both wings. In addition, this method is relatively cheap, fast and easy for fabrication when compared to the expensive MEMS wings [19, 20].

For fabrication, we cut out carbon prepreg into small strips with 1 mm in width. The Kapton film was placed on a paper on which the main venation pattern of a beetle wing was printed. The transparent of the Kapton film is very useful to place the carbon prepreg strips on the film by following the main venation pattern. The resin in the carbon prepreg makes it stick on the Kapton film at the room temperature (25°C), so that the venation pattern can be maintained before curing, as shown in Fig. 2.

After patterning, the artificial wings were then vacuum bagged and cured in an oven with an appropriate profile of temperature [21], shown in Fig. 3, to completely bond the carbon prepreg fibers and the Kapton film together in almost the same pattern as the main wing vein structure of the beetle hind-wing; the venation structure stiffens the wing to sustain the wing loading during flapping motion. The leading edge vein was stiffened by three layers of carbon prepreg strip, and the remaining veins were made of one layer of carbon prepreg strip. We expect that the high elastic modulus of the carbon prepreg fiber will dominate the wing’s structural properties. This fabrication method can be widely and easily applied for different patterns of venation structures. Fig. 4 shows artificial wings after curing: the wing area (9 cm²/wing) and weight (0.075 gram/wing) of the artificial wing are similar to the area (9 cm²/wing) and weight of a real beetle hind-wing (0.065 gram/wing) [8].
3 Experiment and discussion

3.1 Static tests

The initial position where the load is beginning to happen on the wing is hard to be determined because the curvature along the vein is not smooth. Thus, instead of comparing each displacement and load at each measured point, it is better to compare the gradient or slope of the load with respect to deflection at each point rather than the method used in reference [20]. In this work, we compare the wing stiffness of the real beetle hind-wing and biomimetic artificial wing at selected points 1 and 2 on the leading edge; the both wings were subjected to static loading to determine the equivalent stiffness, \( K_{eq} \), at point 1 and point 2 in the chordwise direction as shown Fig. 5 and Fig. 6. Though the wings clearly are not homogenous beams, the overall equivalent stiffness can be calculated by a simple equation,

\[
K_{eq} = \frac{F}{\delta},
\]

where \( F \) is the applied force, and \( \delta \) is the deflection at the measured point.

The apparatus for experiment consists of a laser sensor (Keyence LK-G85) to measure displacement of the wing, a load cell (Kyoto 33FB) to measure force from the wing, a manipulator (Marzhauser DC-3KS) to control the wing displacement. Fig. 7 shows the experimental set-up for static loading test. The wings were glued to a fixture and firmly attached to the manipulator at the wing base. The wing was moved by the micrometer manipulator until it came into contact with an edge-sharpen carbon rod tip mounted on the load cell (Fig. 7). Moving up the wing further applied a point load to the wing; the deflection (\( \delta \)) was measured by the laser sensor, and the applied force (\( F \)) was measured by the load cell.

Table 1 shows a comparison of equivalent stiffness between real beetle hind-wing and biomimetic artificial wing. The biomimetic artificial wing has higher equivalent stiffness than the real beetle hind-wing. At point 1 (51% wing span) and point 2 (36% wing span), the equivalent stiffness of the biomimetic artificial wing is 158.5% and 5.9% higher than that of the real wing, respectively. The larger difference of the equivalent stiffness may be due to the flexible marginal join [16] on the real beetle hind-wing, which could not be mimicked in the biomimetic artificial wing. In addition, the real wing in this case was a dead wing taken from an alive beetle, thus the mechanical property was somehow degraded due to liquid leakage.
Table 1: Comparison of equivalent stiffness between a real beetle hind-wing and biomimetic artificial wing.

<table>
<thead>
<tr>
<th>Wings</th>
<th>( K_{eq} = F/\delta ) (mN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>36 % wing span (Point 2)</td>
</tr>
<tr>
<td>Real Wing</td>
<td>54.11</td>
</tr>
<tr>
<td>Artificial wing</td>
<td>57.28</td>
</tr>
</tbody>
</table>

3.2 Dynamic tests

To compare the natural frequency between the real beetle hind-wing and biomimetic artificial wing, the both wings were subjected to dynamic vibration to measure resonant frequencies. The wing mass was measured by a precise electronic balance with an accuracy of \( \pm 0.1 \) mg (Hansung Electronic Balance Co.). We then painted totally 29 points with white color on a real beetle hind-wing and 25 points on a biomimetic artificial wing, as shown in Fig. 8 and Fig. 9; these dots help the laser sensor catch the deflection of the wing. The wing mass of both wings before and after painting was listed in Table 2.

The apparatus for dynamic test consists of a laser sensor (Keyence LK-G85) to measure displacement of the wing, a shaker (TIRA S153) to apply vibration to the wing, a Bruel & Kjer FFT analyzer to measure frequency response from the wing. Figure 10 shows the experimental set-up for natural frequency measurement. The wing was attached on an acrylic stand fixed on the vibrating base of an electro-mechanical shaker. The laser sensor (Keyence LK-G85) was used to measure the displacement of the wing. The displacement was converted to the analog signal through the laser sensor controller (Keyence LK-GD500) and transferred to the Bruel & Kjer FFT analyzer. The B&K FFT analyzer was used to perform the swept-sine measurements and acquire the displacement analog signal. The range of swept-sine signal was varied from 0 to 400 Hz in this experiment. Then the power amplifier for the shaker was connected to the output of B&K FFT analyzer and responsible for providing sufficient power to the shaker to execute motion at a certain frequency.

Frequency analysis of a beetle hind-wing was conducted on a vibration isolation table to reduce contaminating noise from floor. After gluing the hind-wing onto the shaker base, we adjusted and calibrated the laser sensor so that the laser beam was perpendicular to the plane consisting of one of the painted points on the hind-wing. We initiated the swept-sine function on the B&K FFT analyzer and started to measure the frequency response function at one painted point on the wing. The same procedure was repeated for all 29 painted points for a real beetle hind-wing and 25 painted points for a biomimetic artificial wing. The whole experimental procedure for a real wing was completed within one hour after the wing was severed from the thorax to prevent a change in the mechanical property of the wing due to liquid leakage.

Table 2: Mass of the real beetle hind-wing and biomimetic artificial wing for dynamic test.

<table>
<thead>
<tr>
<th>Wing</th>
<th>Real wing</th>
<th>Artificial wing</th>
</tr>
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<tbody>
<tr>
<td>Wing mass (g)</td>
<td>0.06</td>
<td>0.075</td>
</tr>
<tr>
<td>Wing mass* (g)</td>
<td>0.062</td>
<td>0.090</td>
</tr>
</tbody>
</table>

*Wing mass with painted dots
In this work, we present the experimental results at one of the painted dots. The frequency response function of painted point 1 of the both real beetle hind-wing and biomimetic artificial wing was analyzed and shown in Fig. 11 and Fig. 12, respectively. The fundamental frequency of beetle hind wing was in the order of 47.5 Hz. The second peak predicted as the torsional mode was around 88 Hz. The third peak was 176 Hz. In addition, the flapping frequency of beetle was from 35 to 40 Hz [8], thus it is likely that the higher modes have small effects on the deformation shape of the wing [22].

After inspecting 29 frequency response functions of the 29 painted dots on the real beetle hind-wing, the averaged natural frequencies was identified to 47.5 Hz, 106.7 Hz and 176.6Hz at painted point 1.

The fundamental frequency of artificial wing was in the order of 46.8 Hz. The second peak predicted as the torsional mode was around 126.8 Hz. The third peak was 176.8 Hz. In addition, the flapping frequency of flapper using this artificial wing was about 25 Hz [8]. Therefore, the first three natural frequencies are dominant in characterizing the action of the biomimetic artificial wing. After inspecting 25 frequency response functions of the 25 painted dots on the biomimetic artificial wing, the averaged natural frequencies are identified to 46.8 Hz, 126.80 Hz and 176.9 Hz (first three resonant frequencies) at painted point 1.

4 Conclusions

In this work, we have presented a simple and low cost method for a composite wing fabrication. The biomimetic wing fabricated by this process has a similar weight and area to the real beetle hind-wing. The fabrication method is flexible, thus we can intentionally vary the mechanical properties and wing morphology, which provides a good starting point for experiments investigating the wing flexural stiffness. This wing fabrication process can be modified to create a camber or corrugated wing by using a desired three-dimensional mold. The biomimetic artificial wing has static properties and the first three natural frequencies comparable to the real beetle hind-wing.

Acknowledgments

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References