Effects of deformation and vibration characteristics of wings on flapping flight

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Abstract

The dragonfly wing is passively deformed under flapping and has the strength to withstand high flapping frequency simultaneously. These characteristics of deformation and vibration of the wing are important for flapping flight. However, the effect of these characteristics on flapping flight has not been well understood. The purpose of this study is to investigate deformation and vibration characteristics of the dragonfly wing, and then to develop an artificial wing suitable for flapping flight on the basis of the dragonfly wing. In this study, natural frequency and deformation of the dragonfly wing are measured, and the artificial wing is fabricated on the basis of the results. From the measured results, the dragonfly wing has the high natural frequency of about 120 Hz, and thereby, it does not resonate with flapping. Although base-side of the wing is hardly deformed, the tip-side of the wing is greatly deformed because of the torsional deformation from the nodus of dragonfly wing. On the basis of characteristics of the dragonfly wing, the deformable artificial wing that can deform in the same manner of dragonfly wings was fabricated. Then, aerodynamic force and power consumption under flapping when using the deformable artificial wing was measured. As a result, the power efficiency of aerodynamic force using the deformable artificial wing is five times greater than the power efficiency using a non-deformable wing.

Key words: Dragonfly, Wing, Flapping flight, Vibration, Deformation, Micro Air Vehicle

1. Introduction

There are many creatures that have the unique structure and function optimized for each living environment in the natural world. The structure and function of those biological systems optimized through a long history have many superior characteristics which modern science still hasn’t clarified. The study of applying the structure and function of biological systems to the artificial designing and manufacturing is called biomimetics. Biomimetics have attracted attention in many research fields because clarification of these biological systems improves modern science remarkably. Above all, the flapping MAV (Micro Air Vehicle) modeled on small flying creatures such as insects is developed actively. The small aircrafts with the usual wing form such as fixed-wing or rotary-wing are difficult to fly because small objects are affected by viscous force with scale effect. However, small flying insects can fly at will in spite of that situation. Therefore, the research that shows the flight mechanisms of small flying insects and is for applying it to MAV is increasing.

Among the flying insects, dragonflies are known to have particularly superior flight abilities. Dragonflies can control four wings individually and can make various flights such as fast flight, hovering, quick turn, etc. Moreover, the dragonflies have high robustness, which means continuously flight even if a part of the wing breaks. Many researchers focus on the motility characteristic of dragonflies and had done some study. Some researchers have studied about a flight motion and air flow around flapping wings of dragonflies (Azuma and Watanabe, 1988, Dickinson, et al., 1999, Wang and Russell, 2007, Hu, et al., 2009). Moreover, development of MAV modeled on the dragonfly flight has been

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done in the previous studies (Kosugi and Hashimoto, 2003, Iga and Hashimoto, 2007, Nagai, 2009, Nagai, et al., 2010). Meanwhile, those previous studies have shown that these high flight abilities of the dragonfly are significantly influenced by the characteristics of the wing of the dragonfly such as vibration and deformation. The wing of the dragonfly (the natural wing) has high natural frequencies of more than 100 Hz and is not broken under high flapping frequencies of 30 Hz or over (Chen, et al., 2008). Furthermore, insect wings are passively deformed under flapping, and the effect on generating aerodynamic force by the deformation of the natural wing is pointed out (Nakata and Liu, 2012). Several studies have reported that internal organic junction and vein structure such as corrugation of the natural wing affect stiffness and deformation of the wing (Kesel, et al., 1998, Sunada, et al., 1998, Jongerius and Lentink, 2010, Chen, et al., 2011). As mentioned above, there are several studies about the characteristics of the natural wing. However, the specific effect of these on flight is not well understood. In addition, attaching the natural wing to MAV is very difficult. Therefore, it is necessary to substitute the natural wing with an artificial wing. However, there are no artificial wings with these characteristics so far.

The purpose of this study is to develop the artificial wing suitable for the flapping MAV based on the characteristics of natural wing of dragonflies. In this study, the first natural frequency and the passive deformation under flapping were measured as deformation and vibration characteristics of the natural wing, and then the artificial wing with the same characteristics was fabricated, and the lift and thrust forces generated by flapping were measured. In this paper, the effects of the deformation and vibration characteristics of wings on the flight are reported.

2. Experimental apparatus

In this study, three experiments are carried out. The first experiment is the forced excitation test to measure the first natural frequency of wings. The second one is the test to measure the passive deformation of wings under flapping. Then, artificial wings are fabricated on the basis of these results. The third one is the test to measure the lift and thrust forces of the wings under flapping. Aerodynamic performance of artificial wings fabricated is evaluated with the measurement test of lift and thrust forces.

2.1 Forced excitation test

The first natural frequency of wings is measured with forced excitation test using a vibration exciter. Figure 1 shows the experimental apparatus of forced excitation test. The vibration exciter can vibrate the base of a wing with the cam that is rotated by the motor. The cam is that the rotation axis is off the geometrical center by 0.5 mm. Thereby, the rotary cam provides displacement of 1 mm to the plate mounted above the cam. A test wing is attached to the plate, and then it is vibrated at excitation frequency range from 10 Hz to 190 Hz. The test wing is captured by high-speed camera.
and displacements of the tip and base of the test wing are measured from captured images. After that, amplification ratio $H$ at each excitation frequency is calculated from the two displacements according to the following equation:

$$H = \frac{A}{a}$$

(1)

where $a$ is the displacement of the base; $A$ is the displacement of the tip. The number of the measurement is 5. In addition, the first natural frequency is the excitation frequency of when the amplification ratio reaches a peak.

The test wings used for forced excitation test are three natural wings and three artificial wings. The three natural wings are taken from *Sympetrum frequens*, *Pseudothemis zonata*, and *Orthetrum albistylum speciosum*. Figure 2 shows the structure of the artificial wings. The artificial wings consist of a leading edge and a membrane. The leading edges of the three artificial wings, polyacetal wing, bamboo wing, and carbon wing, were made by different material, polyacetal, bamboo, and carbon-rod, respectively. Table 1 shows density and flexural modulus of each material. Flexural modulus was measured by simplified bending test. Polyacetal and bamboo are 0.55 mm thick and are processed into form of dragonfly wing as shown in Fig.2. Carbon-rod for use in carbon wing is a round bar 0.7 mm in diameter because cutting work of carbon-rod is difficult. The membrane of every artificial wing is made by PET film 50 µm thick.

### 2.2 Measurement test of passive deformation

The passive deformation of a wing is measured using a flapping test machine. Figure 3 shows the flapping test machine. The test machine can flap a test wing by the mechanism below. First, the slider crank mechanism converts rotation of motor to linear reciprocating motion. Next, the lever converts linear reciprocating motion to oscillating motion. Finally, the test wing attached to the end of the lever carries out flapping motion. Although dragonflies are able to perform flapping motion and feathering motion, the test machine mimics only flapping motion because only passive deformation by flapping is measured. A test wing is attached to the test machine, and it is flapped. Next, the flapping test wing is captured by high-speed camera. Then, the angles between a horizontal plane and a line connecting leading edge with trailing edge at three positions of the wing are measured as the deformation from captured images. Figure 4 shows three measurement positions. The test wings used to measure passive deformation are a natural wing and an artificial wing. The natural wing used to measure passive deformation is the wing of *Sympetrum frequens*. Moreover,
the artificial wing that can rotate around the leading edge is fabricated on the basis of finding from measurement results of deformation of the natural wing. Figure 5 shows the structure of this artificial wing. This artificial wing is composed of carbon-rod of leading edge and PET film of membrane. This artificial wing is used for the same measurement.

2.3 Measurement test of lift and thrust forces

Lift and thrust forces generated by flapping are measured by using the flap simulator that was fabricated on the basis of a dragonfly in previous research (Nagai, 2009). Table 2 shows data of the flap simulator. The interval between fore and hind wings is the same as a real dragonfly. Figure 6 shows the variation of flapping and feathering angles of the flap simulator with time. In this figure, cycle $C$ is 0 when hind wings start downstroke. The motion of the flap simulator is based on a straight flight of a dragonfly as shown by dashed lines in fig. 6. Additionally, the flap simulator that performs only flapping motion (feathering angle = 0 [deg]) is also used in the measurement in order to consider the effect of wing deformation on the feathering motion. Figure 7 shows definition of lift and thrust forces in this measurement. The aerodynamic force generated by the straight flight of the dragonfly is divided into lift and thrust. The thrust is defined as the force parallel to the direction of flight, and the lift is defined as the force that is perpendicular to the direction of flight (Fig. 7(a)). The dragonfly flaps wings at an angle to the direction of flight. Accordingly, the flap simulator is put on a triangular base to flap wings at the same angle as the dragonfly. In the case of the flap simulator, the thrust is defined as the horizontal component of the aerodynamic force generated by the flap simulator on the

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Table 2  Data of flap simulator

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<table>
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<tbody>
<tr>
<td>Length of body</td>
<td>85 [mm]</td>
</tr>
<tr>
<td>Wing span</td>
<td>130 [mm]</td>
</tr>
<tr>
<td>Weight of flap simulator (containing DC motor)</td>
<td>53.6 [g]</td>
</tr>
<tr>
<td>Interval between fore and hind wings</td>
<td>4 [mm]</td>
</tr>
<tr>
<td>Mounting angle</td>
<td>30 [deg]</td>
</tr>
<tr>
<td>Angle of wing stroke plane</td>
<td>60 [deg]</td>
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Fig. 6  The variation of flapping and feathering angles of the flap simulator with time
triangular base, and the lift is defined as the vertical component of the aerodynamic force (Fig. 7(b)). Figure 8 shows the experimental apparatus of lift and thrust measurements. Test wings are attached to the flap simulator, and then the flap simulator is driven on the rail and flaps the test wing. Finally, generated thrust is measured by load cell. Stabilized DC power supply is used for driving the flap simulator. In the lift measurement, the direction of lift force makes horizontal by turning the flap simulator 90 degrees. At the same time, voltage and electric current supplied to the flap simulator are measured with a voltmeter and an ammeter. The power consumption of the flap simulator is calculated from the product of voltage and electric current. After that, lift and thrust per power consumption are calculated. Additionally, resistance of wheel and rail is ignored because it is negligibly low.

Fig. 7 Definition of lift and thrust forces

(a) Dragonfly

(b) Flap simulator

Fig. 8 Experimental apparatus of lift and thrust measurements
3. Experimental results

3.1 Results of forced excitation test

Figure 9 shows the results of the forced excitation test of the natural wings, and table 3 shows measurement results of the first natural frequency of the natural wings. In fig. 9, points are the average value, and error bars show error range. From fig. 9, it is decided that the excitation frequency of when the amplification ratio reaches a peak is the first natural frequency. As a result, the first natural frequency of every natural wing used in this measurement was around 120 Hz regardless of the species of the dragonfly. The natural wing doesn’t resonate with flapping frequency because flapping frequency of dragonflies is around 30 Hz. Thus in this study, it is decided that the first natural frequency of the natural wing is 120 Hz, and it is used as the design criteria of artificial wings.

Figure 10 shows the results of the forced excitation test of the artificial wings, and table 4 shows measurement results of the first natural frequency of the artificial wings. The first natural frequency of each artificial wing changed depending on the material of leading edge. Polycetal wing, which used polycetal for leading edge, has lowest first natural frequency of 53.1 Hz. On the other hand, carbon wing, which used carbon-rod for leading edge, has highest first natural frequency, and that is 130.4 Hz, which is similar to the natural wing.

![Fig. 9 Results of forced excitation test of the natural wings](image)

![Fig. 10 Results of forced excitation test of the artificial wings](image)

<table>
<thead>
<tr>
<th>Wing</th>
<th>First natural frequency $\omega$ [Hz]</th>
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<tbody>
<tr>
<td>Pseudothemis zonata</td>
<td>120.0</td>
</tr>
<tr>
<td>Orthetrum albistylum</td>
<td>127.6</td>
</tr>
<tr>
<td>Sympetrum frequens</td>
<td>129.0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Wing</th>
<th>First natural frequency $\omega$ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyacetal wing</td>
<td>53.1</td>
</tr>
<tr>
<td>Bamboo wing</td>
<td>71.4</td>
</tr>
<tr>
<td>Carbon wing</td>
<td>130.4</td>
</tr>
</tbody>
</table>
3.2 Results of passive deformation under flapping

Figure 11 shows measurement results of passive deformation test. This graph shows the angle of passive deformation of the natural wing in one cycle of flapping. As a result, passive deformation of the natural wing was observed. Additionally, the deformation of base part was small; on the other hand, the deformation of tip part was large. Figure 12 shows the shape of passive deformation of the natural wing when cycle \( C \) is 0.3. Figure 12(b) shows illustration tracing of the shape of the wing in the photograph in fig. 12(a), which is out of focus. Moreover, parts of the wing are indicated by arrows to compare the photograph with the illustration. In fig. 12(b), the red, green, and blue dashed lines indicate the chord lines at the tip, the center, and the base of the wing, respectively. It can be seen that the tip part was deformed much larger than the base part. At this time, the deformation angle of the tip part is 40.9 degrees whereas that of the base part is 13.8 degrees. When captured images were observed carefully, it was found that leading edge is twisted from the nodus that is located near the center of leading edge. The nodus is the vein structure unique to dragonflies. Therefore, it is deduced that typical vein structure such as the nodus strongly affects the deformation of a wing.

![Graph](image1)

**Fig. 11** Results of passive deformation test of natural wing

![Illustration](image2)

**Fig. 12** Shape of deformation of natural wing \((C=0.3)\)
On the basis of the above knowledge, the artificial wing that mimics nodus was fabricated. The artificial wing that mimics nodus is easy to twist the tip side of leading edge as explained in fig. 5. From the results of forced excitation test, the artificial wing that mimics nodus is composed of the same material as carbon wing, which has high first natural frequency. In the base side from the center of this artificial wing, the leading edge and the membrane are bonded directly. On the other hand, in the tip side from the center, the leading edge and the membrane are not bonded directly, and the membrane is wrapped around the leading edge. Thereby, the artificial wing that mimics nodus is able to twist only the tip side of wing. Figure 13 shows the measurement results of passive deformation of the artificial wing that mimics nodus, while fig. 14 shows the shape of passive deformation of the artificial wing that mimics nodus when cycle $C$ is 0.3. The deformation of the artificial wing that mimics nodus is similar to the deformation of the natural wing in that the deformation of base is small and the deformation of tip is large. Moreover, the amount of deformation is close to that of the natural wing. Therefore, the deformation of the artificial wing that mimics nodus is the same as the natural wing. 

![Graph](image-url)

**Fig. 13** Results of passive deformation test of artificial wing that mimics nodus

![Diagram](image-url)

**Fig. 14** Shape of deformation of artificial wing that mimics nodus ($C=0.3$)
3.3 Results of lift and thrust under flapping

The lift and thrust forces were measured using the artificial wing that mimics nodus and the carbon wing, which does not deform. The measurement was carried out in 3 cases as follows: attaching the artificial wing that mimics nodus to the flap simulator that does only flapping motion (feathering angle = 0 [deg]), attaching the carbon wing to the flap simulator that does only flapping motion (feathering angle = 0 [deg]), and attaching the carbon wing to the flap simulator that does both of flapping and feathering motions. Figure 14 shows measurement results of lift and thrust in one cycle of flapping when flapping frequency is 30 Hz. As a result, the artificial wing that mimics nodus generates thrust force larger than carbon wing. Table 5 shows the average lift and thrust in one cycle of flapping, and the results of calculating the resultant force when the flapping frequency is 30 Hz. Both the average lift and thrust of the artificial wing that mimics nodus were larger than those of the carbon wing (during flapping motion). Moreover, the resultant force of the artificial wing that mimics nodus was 3 times larger than that of the carbon wing (during flapping motion). In comparison with the carbon wing (during flapping and feathering), the resultant force of the artificial wing that mimics nodus was larger. This result indicates that deformation of the wing contributes to the increase in force that generates aerodynamic forces. However, lift force of carbon wing (flapping and feathering) was larger than that of the artificial wing that mimics nodus.

<table>
<thead>
<tr>
<th></th>
<th>Average thrust $Ta$ [mN]</th>
<th>Average lift $La$ [mN]</th>
<th>Average resultant $Fa$ [mN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial wing that mimics nodus (during flapping motion)</td>
<td>39.5</td>
<td>10.8</td>
<td>40.9</td>
</tr>
<tr>
<td>Carbon wing (during flapping motion)</td>
<td>12.9</td>
<td>2.9</td>
<td>13.2</td>
</tr>
<tr>
<td>Carbon wing (during flapping and feathering)</td>
<td>13.3</td>
<td>21.9</td>
<td>25.6</td>
</tr>
</tbody>
</table>

Fig. 15  Measurement results of lift and thrust under flapping
Figure 16 shows the calculated result of the resultant force per power consumption when the flapping frequency is changed. There was not much difference between the resultant force per power consumption of the carbon wing in flapping only and both of flapping and feathering. On the other hand, the resultant force per power consumption of the artificial wing that mimics nodus was larger than that of the carbon wing in every flapping frequency. When the flapping frequency is 30 Hz, the resultant force per power consumption of the artificial wing that mimics nodus was approximately 5 times larger than that of the carbon wing.

Therefore, the artificial wing that mimics nodus can generate the aerodynamic force more efficient compared to the carbon wing that does not deform. Although generally, the aerodynamic force in flapping flight become greater by adjusting the angle of attack of a wing with active feathering motion, it is suspected that the artificial wing that mimics nodus can automatically adjust the angle of attack without excessive energy usage due to the passive deformation of the wing. However, lift force of the artificial wing that mimics nodus was smaller than that of the carbon wing (flapping and feathering). Continuous studies related to the complicated feathering motion are needed in order to control the direction of aerodynamic force.

4. Conclusions

In this study, the first natural frequency and passive deformation of the natural wing was measured. On the basis of measurement result of characteristics of the natural wing, the artificial wings with the same characteristics were fabricated and tested. The lift and thrust forces under flapping were measured, and the performance of the artificial wings fabricated was evaluated. The results are summarized as follows:

1) The natural wing has high first natural frequency of about 120 Hz, therefore, it does not resonate with flapping frequency.
2) Because the leading edge of the natural wing is twisted from the nodus, the deformation of the base of the wing is small, and the deformation of the tip is large.
3) Using a carbon-rod for a material of the leading edge, the artificial wing is able to have the high first natural frequency similar to the natural wing. It also does not resonate with flapping frequency.
4) When using the artificial wing that mimics nodus, which is easy to twist the tip side of the wing, the aerodynamic force per power consumption is five times larger than that of the carbon wing, which does not deform. Therefore, the artificial wing designed to deform similarly to the natural wing can generate the great aerodynamic force with high efficiency.
References


