Development of the Artificial Wing Suitable for Flapping Micro Air Vehicle Based on Dragonfly Wing

Hisayoshi NAKA*[1], Yuta SUNAMI*[2], and Hiromu HASHIMOTO*[3]

*1 Graduate School of Engineering, Tokai University
4-1-1, Kitakaname, Hiratsuka City, Kanagawa Prefecture 259-1292, JAPAN
3bmkm038@mail.tokai-u.jp

*2, 3 Department of Mechanical Engineering, Tokai University
4-1-1, Kitakaname, Hiratsuka City, Kanagawa Prefecture 259-1292, JAPAN
sunami@tokai-u.jp, hiromu@keyaki.cc.u-tokai.ac.jp

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 is important for dragonfly flight. However, the effect of those on dragonfly flight has not been well understood. The purpose of this study is to develop an artificial wing suitable for flapping Micro Air Vehicle on the basis of the dragonfly wing. Therefore, natural frequency and deformation of the dragonfly wing are measured, and the artificial wing is fabricated on the basis of result of that. From the results of measurement, the dragonfly wing has the high natural frequency of 120 Hz. 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. Then, the deformable artificial wing which can deform in the same manner of dragonfly wings was fabricated, and aerodynamic force and power consumption under flapping was measured. As a result, the power efficiency of aerodynamic force using the deformable artificial wing is 5 times greater than the power efficiency using an undeformable wing.

Keywords: Dragonfly, Wing, Vibration, Deformation, Micro Air Vehicle

1 Introduction

In recent years, biomimetics that is the study of applying the structure and function of biological systems to the designing and manufacturing has attracted attention. The structure and function of biological systems optimized through a long history have many superior characteristics which modern science still have not clarified. Because of clarifying these improves modern science remarkably, biomimetics have been studied in many fields. Above all, the flapping MAV (Micro Air Vehicle) modeled on small flying creatures such as insect is developed actively. Because small objects are affected by viscous force with scale effect, the small aircrafts with the usual wing form such as fixed-wing or rotary-wing are difficult to fly. However, small flying creatures can fly at will in spite of that situation. Therefore, the research of clarifying the flight mechanisms of small flying creatures and then applying it to MAV is proceeding.

There are many flying insects in the natural world. Among the flying insects, dragonflies are known to have particularly superior flight abilities. Dragonflies can control four natural wings individually and can make various flights such as fast flight, hovering, quick turn, etc. Moreover, the dragonfly has high robustness which means continuously flight even if part of the natural wings break. 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 [1]-[4]. Moreover, development of MAV modeled on the dragonfly flight has been done in the previous studies [5]-[8]. Meanwhile, those previous studies have shown that these high flight abilities of the dragonfly are significantly influenced by characteristics of the natural wing such as a vibration and a deformation also. The natural wing of the dragonfly has high natural frequencies of more than 100 Hz and is not broken under high flapping frequencies of 30 Hz or over [9]. Furthermore, the insect wing is passively deformed under flapping, and the effect on generating aerodynamic force by the deformation of the natural wing is pointed out [10]. Several studies have reported that internal organic junction and vein structure such as corrugation of the natural wing affects stiffness and deformation of the wing [11]-[14]. 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 an artificial wing for the natural wing, however, there are no artificial wing 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 the 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 lift and thrust force generated under flapping were measured. We report the effect of the deformation and vibration characteristics of wings on the flight.

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 experiment is the measurement test of passive deformation to measure the passive deformation of wings under flapping. Then, artificial wings are fabricated on the basis of results of those. The third experiment is the measurement test of lift and thrust force to measure the lift and thrust force of when wings are flapped as a dragonfly. Aerodynamic performance of fabricated artificial wings is evaluated with the measurement test of lift and thrust force.

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. A test wing is attached to the vibration exciter and then 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 is measured from captured images. After that, amplification ratio H at each excitation frequency is calculated from the two displacements according to the following equation:

$$H = \frac{A}{a} \tag{1}$$

where a is the displacement of the base; A is the displacement of the tip. The first natural frequency is the excitation frequency of when the amplification ratio reach a peak.

The test wings used to 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 wing. The artificial wing consists of a leading edge and a membrane. The leading edges of 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 flapping 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 movement.

Table 1 Property of materials of the leading edge

Material	Density [g/cm^3]	Flexural modulus [MPa]
Polyacetal	1.41	2600
Bamboo	0.558	10900
Carbon-rod	1.43	120000

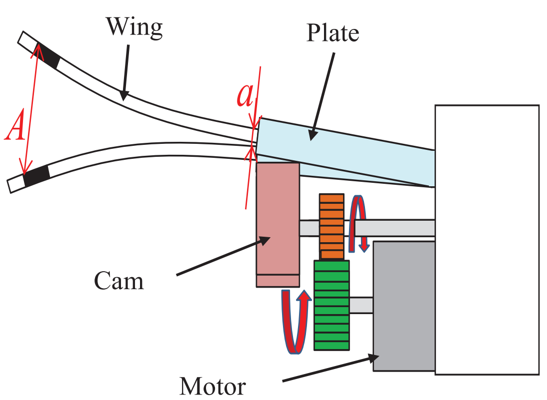


Fig. 1 Experimental setup of excitation test

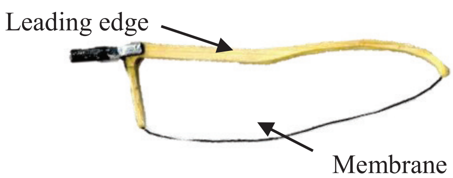


Fig. 2 Structure of artificial wing

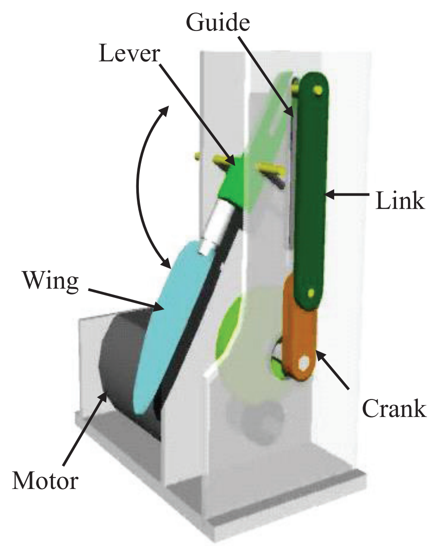


Fig. 3 Flapping test machine

Finally, the attached test wing to the end of the lever carries out flapping motion. Although a dragonfly is able to perform flapping motion and feathering motion, the flapping test machine mimics only flapping motion because only passive deformation by flapping is measured. A test wing is attached to the flapping 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 of three positions of the wing are measured as the deformation from captured images. **Figure 4** shows three measurement positions. The test wings used to measurement of passive deformation are a natural wing and an artificial wing. The natural wing used to measurement of passive deformation is the wing of *Sympetrum frequens*. Moreover, an artificial wing that can rotate around the leading edge is fabricated on the basis of finding from measurement result of deformation of natural wing. **Figure 5** shows the structure of this artificial wing. This artificial wing is used to same measurement.

2.3 Measurement test of lift and thrust force

Lift and thrust force under flapping are measured by using flap simulator that mimics only flapping motion with the same structure as the fabricated simulator based on a dragonfly in previous research [7]. **Figure 6** shows the experimental setup of lift and thrust measurement, and **Table 2** shows data of the flap simulator. Phase difference, flapping angle, and mounting angle are set based on free flight of dragonfly. Because dragonflies flap wings at an angle, the flap simulator is put on a triangular base for flapping at the same angle. Test wings were attached to the flap simulator, and then the flap simulator was driven on the rail and flapped the test wing. Finally, generated lift or thrust was measured by load-cell. At the same time, power consumption of the flap simulator is measured, and lift and thrust per power consumption is calculated. Additionally, resistance of wheel and rail is ignored because it is vanishingly low.

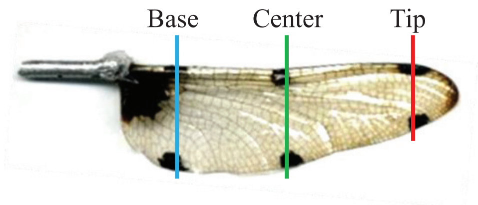


Fig. 4 Measurement position

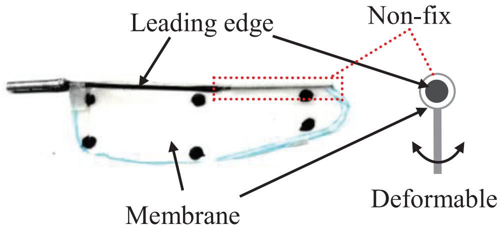
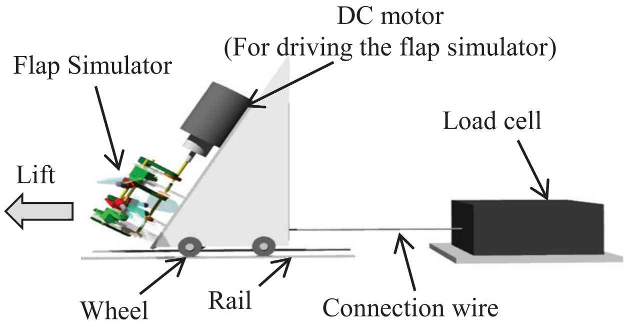
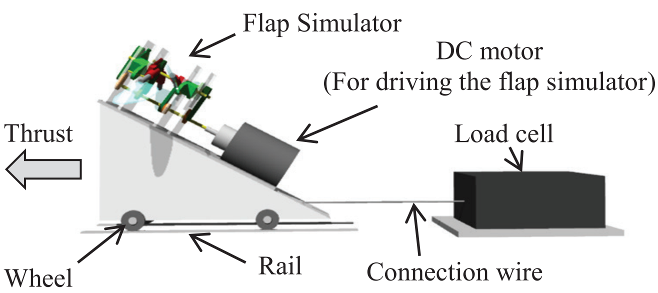


Fig. 5 Artificial wing that mimics nodus



(a) Lift measurement



(b) Thrust measurement

Fig. 6 Experimental setup of lift and thrust measurement

Table 2 Data of flap simulator

Length of body		85 [mm]
Wing span		130 [mm]
Weight of flap simulator (containing DC motor)		53.6 [g]
Interval between fore and hind wings		4 [mm]
Phase difference between fore and hind wings		290 [deg]
Flapping angle	Fore	60 [deg]
	Hind	80 [deg]
Mounting angle		30 [deg]

3 Experimental results

3.1 Results of forced excitation test

Figure 7 shows the result of the forced excitation test of the natural wings, and **Table 3** shows measurement results of the first natural frequency of the natural wings. The first natural frequency of every natural wing was around 120 Hz regardless of species. Because flapping frequency of a dragonfly is around 30 Hz, a natural wing does not resonate with flapping frequency. For this result, we decided that first natural frequency of the natural wing is 120 Hz in this study, and it is used as design criteria of artificial wings.

Figure 8 shows the result 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. Polyacetal wing, which used polyacetal to leading edge, has lowest first natural frequency of 53.1 Hz. On the other hand, carbon wing, which used carbon-rod to leading edge, has highest first natural frequency, and that is 130.4 Hz, which is similar to the natural wing.

3.2 Results of passive deformation under flapping

Figure 9 shows measurement results of passive deformation test. **Figure 9(a)** shows 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 9(b)** shows the shape of passive deformation of the natural wing when cycle C is 0.3. It can be seen that the tip part was deformed 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. We observed captured image carefully, and it was found that leading edge is twisted from the nodus that is located near the center of leading edge. The nodus is vein structure unique to a dragonfly. Therefore, it is deduced that typical vein structure such as the nodus affects the deformation of a wing.

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 explained in **Fig. 5**. The leading edge of the artificial wing that mimics nodus is carbon-rod that exhibits 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 10** shows measurement results of passive deformation of the artificial wing that mimics nodus. 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.

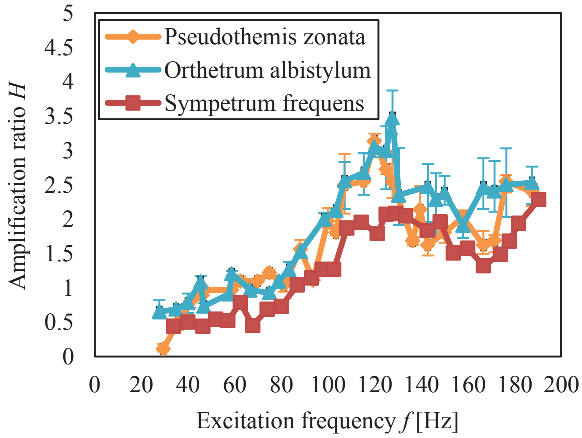


Fig. 7 Results of forced excitation test of the natural wings

Table 3 Results of the first natural frequency of the natural wings

Wing	First natural frequency ω [Hz]
Pseudothemis zonata	120.0
Orthetrum albistylum	127.6
Sympetrum frequens	129.0

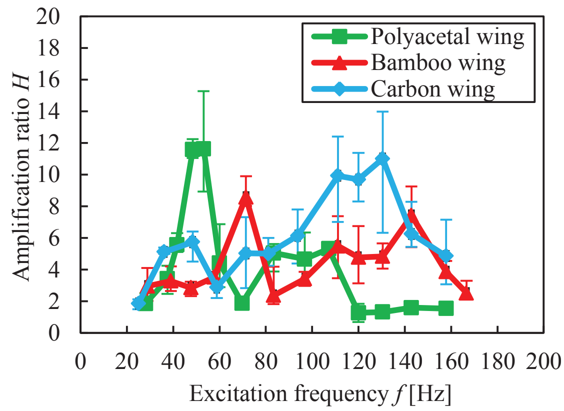


Fig. 8 Results of forced excitation test of the artificial wings

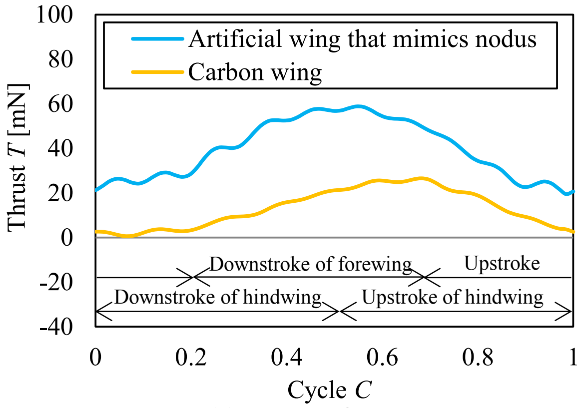
Table 4 Results of the first natural frequency of the artificial wings

Wing	First natural frequency ω [Hz]
Polyacetal wing	53.1
Bamboo wing	71.4
Carbon wing	130.4

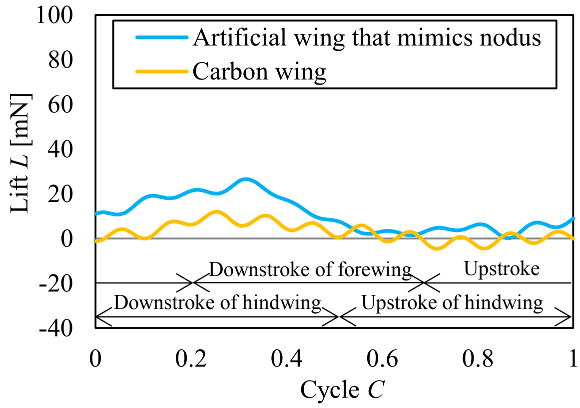
3.3 Results of lift and thrust under flapping

The lift and thrust force when using the artificial wing that mimics nodus was compared with when using the carbon wing that does not deform. **Figure 11** shows measurement result of lift and thrust in one cycle of flapping. As a result, the artificial wing that mimics nodus generates aerodynamic force larger than carbon wing. In particular, thrust force of the artificial wing that mimics nodus is very high during flapping. **Table 5** shows the average lift and thrust in one cycle of flapping when flapping frequency is 30 Hz, and the results of calculating the resultant force. Both the average lift and thrust of the artificial wing that mimics nodus were larger than those of the carbon wing. Moreover, the resultant force of the artificial wing that mimics nodus was 3 times larger than that of the carbon wing. This result indicates that deformation of the wing contributes to raise the generating aerodynamic force.

Figure 12 shows the calculating result of the resultant force per power consumption when the flapping frequency is changed. 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 of the artificial wing that mimics nodus was 5 times larger than that of the carbon wing. Therefore, the artificial wing that mimics nodus can generate the aerodynamic force more efficient than the carbon wing that does not deform. Although the aerodynamic force in flapping flight become greater by adjusting the angle of attack of a wing with active feathering motion generally, it is suspected that the artificial wing that mimics nodus can automatically adjust the angle of attack without excess energy by passive deformation of the wing.

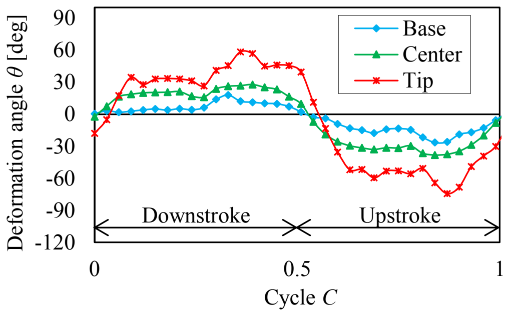


(a) Thrust force

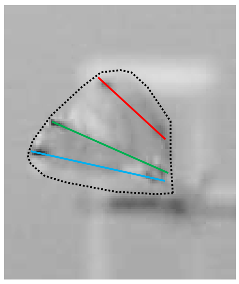


(b) Lift force

Fig. 11 Measurement result of lift and thrust under flapping

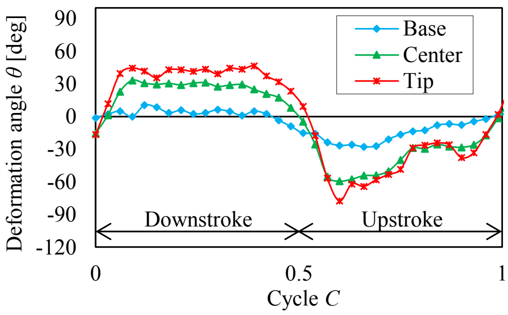


(a) Passive deformation of natural wing in one cycle of flapping

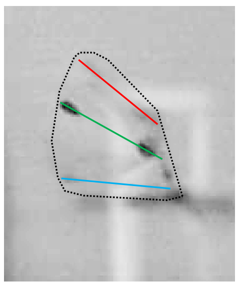


(b) Shape of deformation (C=0.3)

Fig. 9 Result of passive deformation test of natural wing



(a) Passive deformation of artificial wing in one cycle of flapping



(b) Shape of deformation (C=0.3)

Fig. 10 Result of passive deformation test of artificial wing that mimics nodus

4 Conclusions

In this study, the first natural frequency and passive deformation of the natural wing of a dragonfly was measured. On the basis of measurement result of characteristics of the natural wing, the artificial wings with the same characteristics was fabricated. Then, the lift and thrust force under flapping was measured, and the performance of the fabricated artificial wings was evaluated. These result are summarized as follows:

(1) The natural wing has the 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 to a material of the leading edge, an artificial wing is able to have the high first natural frequency similar to the natural wing. It 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 5 times larger than that of the carbon wing. Therefore, the artificial wing designed to deform similarly to the natural wing can generate the great aerodynamic force with high efficiency.

Table 5 Results of lift and thrust measurement

	Artificial wing that mimics nodus	Carbon wing
Average thrust T_a [mN]	39.5	12.9
Average lift L_a [mN]	10.8	2.9
Average resultant F_a [mN]	40.9	13.2

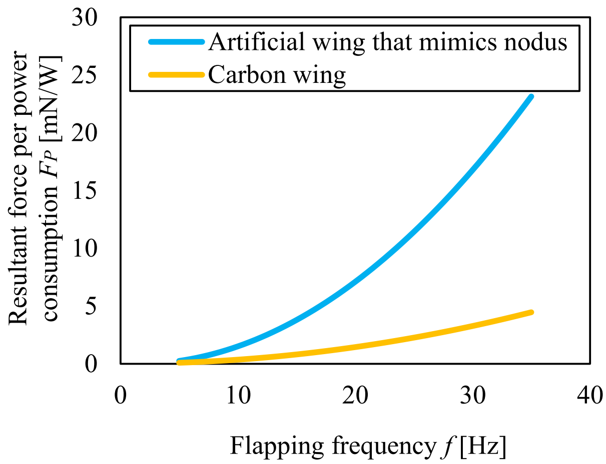


Fig. 12 Relation of resultant force per power consumption and the artificial wing that mimics nodus

References

[1] Akira Azuma, Tadaaki Watanabe, "Flight Performance of a Dragonfly", The Journal of experimental biology 137, (1988), pp.221-252.
[2] Michael H. Dickinson, Fritz-Olaf Lehmann, Sanjay P. Sane, "Wing rotation and the aerodynamic basis of insect flight", Science 284, (1999), pp.1954-1960.
[3] Z. Jane Wang, David Russell, "Effect of Forewing and Hindwing Interactions on Aerodynamic Forces and Power in Hovering Dragonfly Flight", Physical Review Letters 99, (2007), 148101.
[4] Zheng Hu, Raymond McCauley, Steve Schaeffer, Xinyan Deng, "Aerodynamics of Dragonfly Flight and Robotic Design", IEEE International Conference on Robotics and Automation, (2009), pp.3061-3066.
[5] Kei Kosugi, Hiromu Hashimoto, "Development of Mini-Sized-Robot Based on Flight Mechanics of Dragonfly", JSME annual meeting, 2003(5), pp.89-90.
[6] Kosuke Iga, Hiromu Hashimoto, "Development for MAV of Dragonfly's Wing Motion: Flight Motion Photographs and Visualization on Unstationary state", JSME annual meeting 2007(6), pp.97-98.
[7] Nagai Satoshi, "Development of Wing Motion Simulator with Dragonfly's Wing Interval", JSME annual meeting, 2009(4), pp.105-106.
[8] Satoshi Nagai, Shinya Koseki, Hiromu Hashimoto, "Experimental Study of Vortex Generating Mechanism of Dragonfly's Wing", JSME annual meeting 2010(6), pp.47-48.
[9] Jen-San Chen, Jeng-Yu Chen, and Yuan-Fang Chou, "On the natural frequencies and mode shapes of dragonfly wings", Journal of Sound and Vibration 313, (2008), pp.643-654.
[10] Toshiyuki Nakata, Hao Liu, "A fluid-structure interaction model of insect flight with flexible wings", Journal of Computational Physics, Volume 231, Issue 4, (2012), pp.1822-1847.
[11] Antonia B. Kesel, Ute Philippi, Werner Nachtigall, "Biomechanical aspects of the insect wing: an analysis using the finite element method", Computers in Biology and Medicine 28, (1998), pp.423-437.
[12] Shigeru Sunada, Lijiang Zeng, Keiji Kawachi, "The Relationship Between Dragonfly Wing Structure and Torsional Deformation", Journal of Theoretical Biology, Volume 193, Issue 1, (1998), pp.39-45.
[13] S. R. Jongerius, D. Lentink, "Structural Analysis of a Dragonfly Wing", Experimental Mechanics, Volume 50, Issue 9, (2010), pp.1323-1334.
[14] Chen YingLong, Wang XiShu, Ren HuaiHui, Li XuDong, "An organic junction between the vein and membrane of the dragonfly wing", Chinese Sci Bull, Volume 56, Issue 16, (2011), pp.1658-1660.

Received on December 31, 2013
Accepted on February 14, 2014