Development of the Flight Performance of a 15 cm Flapping-wing Air Vehicle

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ABSTRACT

This study focuses on the development of the flight performance of the 15 cm flapping air vehicle, which is being developed in Konkuk University. The modification on the wing structure and material is carried out to gain better performance compared to its predecessor. The effects of wing frame structure material characteristics variation was analyzed in a wind tunnel and vacuum condition experiments to measure the vertical force produced by the system. Both tests were conducted with the control surface fixed in a neutral position and flapping motion is supported by a motor at a constant setting. Smoke-wire flow visualization is also conducted to confirm the generation of leading edge and trailing edge vortices.

1 INTRODUCTION

A lot of researches have been carried out to study the flapping flight in recent years, from natural flyers to man-made flapping-wing air vehicle. The development of a flapping-wing air vehicle has been very much affected by its natural counterparts. By analyzing the kinematic, aerodynamic, and flight performances of the flapping-wing vehicle, which adopting the flight mechanism of the flying animals we are able to modify the performance of the vehicles.

There are two types of mechanism that will be explored throughout this paper. First is the mechanism of wing clap which was proposed by Weis-Fogh as a methodology of lift enhancement during insect flight [1]. During clap, the leading edges of the wings touch each other before the trailing edges, thus the gap is getting narrower between them. As the wings closely press together, the opposing circulations of each wing cancel out each other. This mechanism becomes the reason of high lift generation in the tiny insects.

The other development is proposed by modifying the wing frame structure to mimic that of insect structure. By specifically mimicking the vein structure for a slow forward flight, it has been studied that it influenced the aerodynamic performance of a butterfly-mimicking flapping-wing air vehicle [2]. A biomimetic design of a cicada wing has also proved to enhance the lift and thrust generation [3].

The objective of this study is to increase the flight performance, in terms of increasing the flight endurance of the flapping system. The new flapping-wing air vehicle was tested by modifying the frame structure and skin material of the wing. Different wings were fabricated with different frame structure and skin material. The effect of the stiffness of the wings on the flight characteristics was investigated. A high-speed video camera was used to support the analysis of flight attitude and force measurement.

In 2008, the development of 15 cm KU-Ornithopter was started. The flapping frequency of the vehicle was modified due to the RPM control of the motor and result of T-tail system with solely vertical stabilizer. The total force generated by the wing was not sufficient to fly under wind velocity over 2 m/s, so most of flight tests were conducted indoor. It was ranked at the 3rd place for the indoor dynamic mission at the EMAV Flight Competition 2008 in Braunschweig, Germany. The specification of the vehicle is given in Table 1.

Parameter	Value
Wing Span	15 cm
Wing Area	85 cm^2
Weight	8.7 g
Fuselage Length	15 cm
Frequency	30 Hz
Flapping angle	45°
Flight duration	1 min
Battery	Li-Poly (60 mAh)

Table 1: Original flapping-wing air vehicle specification

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2 MODEL PREPARATION

2.1 Design

The wing structure variation was made by developing two different frame structures and two different skin materials. The frame structures were differentiated by having a normal wing and a modified wing, which is a biologically inspired wing structure mimicking the vein structure of a horse fly. The modified wing was made by tracing the lines of the outer horsefly wing, then simplifying the vein structure to be implemented as wing frame for the vehicle. Table 2 shows the material variation.

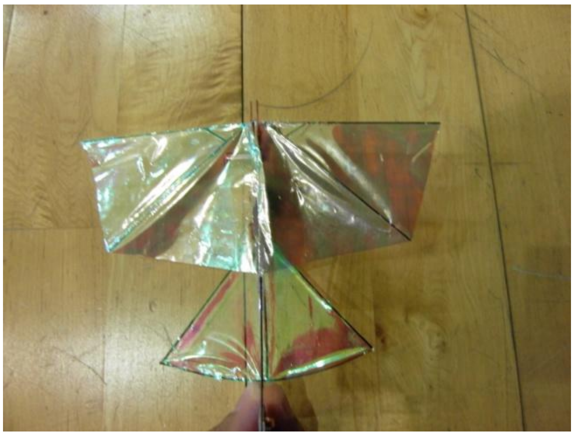

Figure 1: Original 15 cm Flapping-wing Air Vehicle

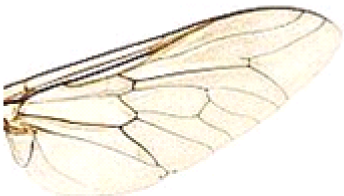

Figure 2: Horsefly Wing Structure

Type	Material	Thickness
Type A	PET Film	0.02 mm
Type B	Kapton Film	0.007 mm

Table 2: Wing material variation

2.2 Fabrication

All types of wings were manually fabricated. The original type of the wing was composed of PET film as the skin and carbon/epoxy rod as the skin frame. The modified skin frame was later changed to carbon/epoxy frame lay-up at thickness 0.8 mm. The second type of the wing with Kapton film with wing frame also used carbon/epoxy rod. Yet for the modified frame structure, the carbon/epoxy fibers and kapton film were vacuum bagged and cured in an autoclave at high temperature (177°C) to them perfectly bond together [4]. The summary of the models shows by Table 3.

Wing Type	Frame	Material
Type 1	normal	Type A
Type 2	normal	Type B
Type 3	modified	Type A
Type 4	modified	Type B

Table 3: Wing Variations

3 EXPERIMENT

3.1 Flapping Test

The test was conducted in a wind tunnel with 1 m (height) × 1 m (width) × 3 m (length) dimension. The tunnel was operated at a varied wind speed ranging from 2 m/s to 6 m/s.

The flapping tests were performed to examine the influence of wing modification to the vertical force produces by the flapping-wing vehicle. The measured vertical force composes of aerodynamic force and inertia force [4].

The vertical force was measured by using a bending-type load cell (Nano 17). The vertical force measurement was conducted by collecting the experimental data of the force measured in the air (wind tunnel) and vacuum conditions. The aerodynamic force, then, can be calculated by subtracting the inertia force, which is measured in the vacuum condition from the total force from the air condition. The experiment in the air condition was conducted by preparing the wings to be tested under applying voltage 7.4 V. To adjust the flapping frequency and amplitude during the flight in the vacuum condition, the input voltage was adjusted so that the force calculated in the vacuum condition can be regarded as the inertia force of the vehicle in the air. The preparations for the experiments are shown by Figure 3 and Figure 4.

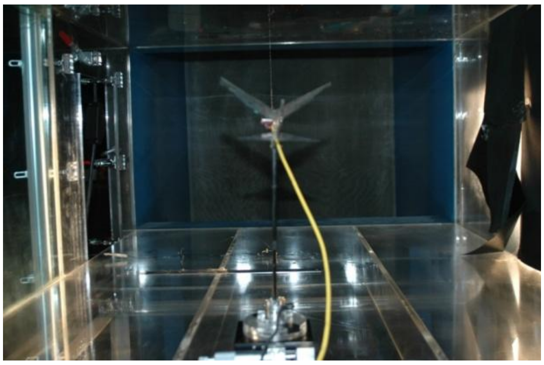

Figure 3: Wind tunnel experiment setup

Figure 4: Vacuum condition experiment setup

3.2 *Free Flight Test*

This test was conducted to analyze the flight attitude and velocity of the flapping-wing air vehicle. The experiment setup for the free flight test is shown in Figure 5.

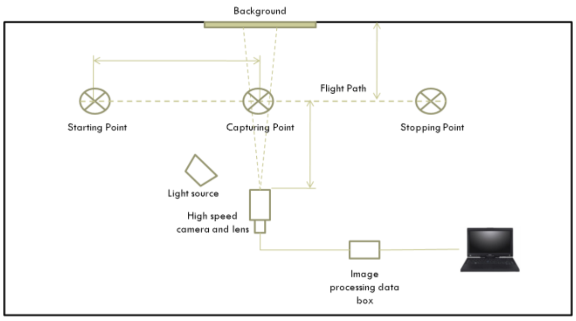

Figure 5: Free flight setup.

4 RESULTS

4.1 *Mass and CG*

The longitudinal position of the CG for the stable flight was set by adjusting the longitudinal position of the balance weight. On the other hand, the perpendicular position of the CG was determined by calculating the ratio of the mass of the wings to the mass of other components. These characteristics influence the flight attitude of the vehicle.

4.2 *Wing Structure Modification*

The effects of the wing structure variations were analyzed to show their influence to the flight performance of the flapping-wing air vehicle. The effect of adopting clap mechanism by varying different skin materials and wing frames were examined by separating the examinations of inertia and aerodynamic forces.

The measurement was conducted in two different environments, namely air and vacuum conditions. The earlier condition measured the total force, while the latter measured the inertia force. Synchronization of the total force and inertia force was then carried out to calculate the aerodynamic force by subtracting the inertia force from total force. Here, the vertical force is the only one to be considered. The results of the measured average vertical forces for the specimens are given in Figure 4.

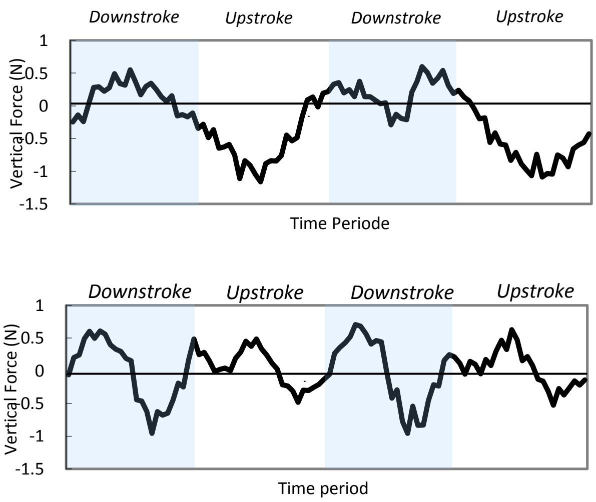

Figure 6: Characteristics of measured vertical force: Original (top); horse botfly (bottom)

The biomimetic specimens have different shapes and wing area that contributed to the force that they produced during flapping. Horse botfly shared almost the same shape with rounded tip. However, they were different on the leading edge shape. The horse botfly shape was rather having a small swept angle. This shape then believed to highly contribute to the vertical force as suggested by Figure 7.

One of the main features of the biomimetic wings, namely different thickness throughout the wing root to wing tip was applied to all of the biomimetic structures. The thickness difference however was only kept at the leading edge to the trailing edge by varying the thickness of the carbon/epoxy ply. As all biomimetic wing has the same thickness distribution throughout wing root to wing tip, this feature was not considered to have a big effect on the force generation.

Next feature is the cell-type membrane. By observing the biomimetic design, we may see that horse botfly has a small and packed cell-type membrane. This feature is believed to contribute to the vertical force generation. In this study, the packed cell-type wing structures tend to give more weight due to the extra plies that needed to fully form a cell.

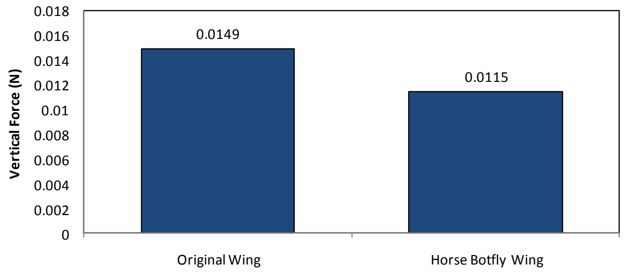

Figure 7: Vertical forces of non-cambered original flapping wing

4.3 *Flight Attitude and Velocity*

The average body angle θ per flapping vehicle is measured, as well as the average angle of attack of attack at the base, α_{base} , per flapping cycle. The velocities in the flight coordinate system are also measured. By having these parameters measured, each flight performance of flapping-wing air vehicle can be analyzed and compared.

The measurement was conducted indoor to test the flight performance of the flapping-wing micro air vehicle which uses two different wings: original and biomimetic wings. The experiment was also recorded by high speed camera with the experiment configuration shown in Figure 5 to measure the flight kinematics and body angle of the vehicle during flight.

The first test was conducted for the original wing which was able to fly with flight angle 17° at the speed of 3.62 m/s. This result however was not successfully obtained from the flapping-wing micro air vehicle with the biomimetic wing. Therefore some improvement is still being conducted to improve the performance of the biomimetic design to be able to fly.

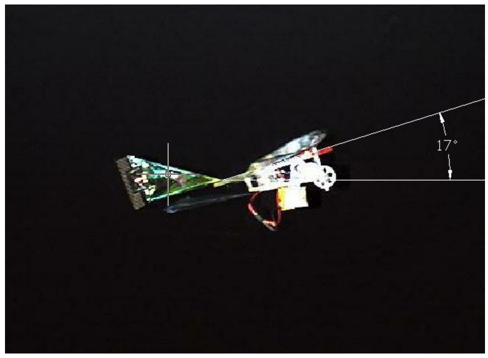

Figure 8: Free Flight Test Result for original wing

4.4 *Flow Visualization*

Smoke-wire visualization was carried out to verify the generated leading and trailing edge vortices. The images of the air flow were captured with a Photron FASTCAM high-speed camera operated at 2000 fps. The three types of the wings were also tested at different values of flapping angle.

Leading edge vortex (LEV) is one of the representative features of unsteady flight. The presence of the vortex on top of the wing will enhance lift production. As shown in Figure 9, the flow visualization confirmed the leading and trailing edge vortices that contributed to the force generation. Figure 9 (c) and (d) show that the biomimetic hawkmoth wing generated relatively strong leading and trailing edge vortices during flapping.

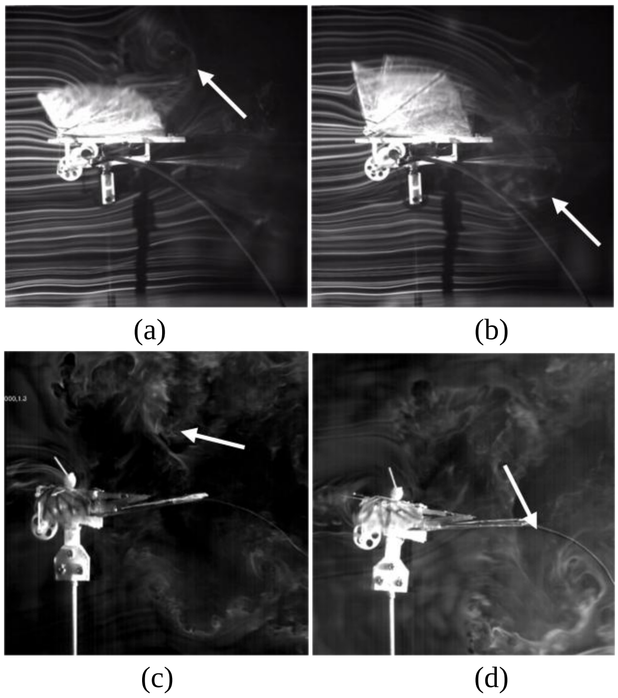

Figure 9: Flow Visualization for the original wing and biomimetic wings

5 CONCLUSION

The modification of wing structure was carried out to develop the flight performance of the flapping-wing air vehicle, in terms of increasing the flight endurance of the flapping-wing air vehicle. The stiffness of the wing is expected to influence the performance. The concept of biomimetic wing was introduced by adopting two main features of insects (horse botfly), namely different thickness distribution throughout wing root and wing tip and cell-type membranes. The vertical force was analyzed. The effects of the adoption of the two main features were also experimentally investigated. However, to have a better investigation of the biomimetic wing structure, a more detailed study is still needed.

ACKNOWLEDGMENT

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