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Investigation on Flow Visualization of Beetle Mimicking Ornithopter

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ABSTRACT--- ***A scale up model of beetle mimicking ornithopter, an autonomous flapping-wing micro air vehicle (MAV) is developed emulating an established model. The ornithopter model used for this purpose is developed by a team from Department of Aerospace and Information Engineering, Department of Advanced Technology Fusion and National Research Laboratory for Biomimetics and Intelligent Microsystems of the Konkuk University, Korea. We scale up the model double its original size of length 128 mm. In reality, initial design of an ornithopter is not from a certain pre-set specifications as it depends on weight, duration of battery, stability and material. The design is based on trial and error with an approach of not knowing the characteristics and performance of the wing mechanism beforehand. The wing morphology of the beetle is studied for identifying the size and weight of the model. The development of the scale up flapping wing is intended for the study of the flow visualization in a low speed wind tunnel experiment. The preliminary study on the flow visualization of the ornithopter showed some interesting patterns. Although the flow patterns are not the best of quality, however, one can see that the ornithopter generates vortices as it flaps its wing in the upstroke motion as well as in the downstroke motion. These study from the wind tunnel test will be investigated and evaluated to give some preliminary idea on the flow patterns of the ornithopter for simulating necessary aircraft load to validate the ornithopter performance in the future works.***

Keywords- beetle mimicking ornithopter; scale up model; wind tunnel test; flow visualization

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1. INTRODUCTION

The flight envelope of MAVs requires high agility (including hover) at low speeds (a few mph) and silent flight, which does not make scaled down fixed wing aircraft or rotorcraft attractive. Therefore, insect-like flapping flight seems to be an optimal mode of flying for highly manoeuvrable flight through confined spaces (1). This mode of flying relies on unsteady aerodynamics (2), producing high lift coefficients (peak CL of the order of 3 is typical (3)) and excellent manoeuvrability. The ornithopter has been known for its unique feature compared to conventional unmmaned aerial vehicle. The ornithopter generates lift and thrust for forward, hovering motion using their flapping-wings, emulating birds or insects. However, designing flapping-wing vehicles just by mimicking the flight of birds or insects is insufficient. It has two major problems, consisting of developing the structure of ornithopter and the developing the autonomous system for the vehicle.

It is of the interest of many researchers to explain flapping mechanism in hovering flight, forward flight, and remarkable maneuvering flight of flying animals (4). However, developing a working insect-like flapping wing micro aerial vehicle (FW-MAV) is tremendously difficult task to perform compared to fixed or rotary wing aircraft (5)(6). It has been recognized recently that flapping wing propulsion can be more efficient than conventional propellers if applied to MAV, because of the very small Reynolds numbers encountered on such vehicles (5)(7) as the fixed wing designs encounter fundamental challenges in low lift-to-drag-ratio and unfavorable flight control (7). The flapping-wing technology is therefore, considered to be the most potential solution for the micro aerial vehicle (MAV).

Study in the flow visualization on the flapping wing system is very imperative in order to develop insect-like flapping wing MAV. Little is known on the complex three dimensional dynamic structures of leading egde vortex (LEV) and spanwise flow produced by these insects (8). Flapping wing such as in insects have deformable structure and can change the wing shape as a function of angle of attack and unsteady aerodynamic forces (8). A lot of study has been carried out to understand the flow physics of such flight. It is done by smoke flow visualization over flapping wing in a wind tunnel, by PIV for the dynamics of these vortices dominated flows and by dye flow visualization in water tank (9). Significant observations have been made in identifying the important governing parameters like Reynolds number (Re) range and phenomena like the leading edge vortex domination of these flights deterring the flow separation, wake capture, clap and fling (9).

2. OVERVIEW OF THE BEETLE MIMICKING ORNITHOPTER

Insect-like Flapping Motion

In the conventional aircraft, a propeller is used for generating thrust, and fixed wing for lift forces. The ornithopter's wing must provide both of these fundamental forces. In addition, the forces on the ornithopter's wing vary throughout the flapping cycle, and the formation of wing as well. Insects fly by oscillating (frequency range: 5 – 200 Hz) and rotating their wings through large angle as it is not limited by internal skeleton (10). The wing beat cycle can be divided into two distinct phases, the downstroke and the upstroke. On the downstroke maneuver, air is displaced in a downward and backward direction, so that the angle of attack changes noticeably during this motion (10). At the most downwards position, the wing is twisted rapidly and the leading edge points backwards. Meanwhile, during the upstroke, the wing is pushed upwards and at the highest point the wing is twisted again (10). On the upstroke maneuver, in order to make a positive global lift, the situation is reversed being the area of the wing is smaller than before. In order to make the area of the wing smaller, birds or insects use different techniques, such as manipulating the form of the wing. The downstroke lasts longer than the upstroke in forward flight for producing thrust and in hover they are equal (10).

Beetle Mimicking Ornithopter

A beetle-mimicking flapping wing developed by a team from Konkuk University, Seoul, Korea becomes an interest for this research. The beetles of species *Allomyrina dichotoma* from *coleopteran* order have large body size and two pairs of wing: elytra (outer wings, fore wings) and hind wings (inner wings) (4)(6). The deployment mechanism of the hind wing involves the unfolding motion of the wing structure triggered by actuation of muscles in the body of the beetle. It also needs to swing its whole wing member around the wing joint to deploy the hind wings (6). The hind wing of the beetle have a folding ratio of 2.3, meaning that it can expand its surface area more than two times larger in unfolded configuration from the folded configuration (6).

The study of wing kinematics of the beetle is important as the aerodynamic force generated by the wings can be computed. The flapping wing system of the beetle developed can flap its wings at a frequency of 37 Hz with a designated flapping angle of 160° which are similar to those of the real beetle (11). The supporting frames and linkages parts used a 0.8 mm thick glass/ epoxy sheet which was fabricated by a precision CNC machine from AutoCAD software design (11). The wing however were made of carbon prepreg strip and thin Polypropylene and were directly connected to the output links at the root of the leading edge veins. The trailing edges of the wings near wing roots were connected to the installed motor so that the wings can be twisted from root to tip during the flapping motion (11).

3. FLAPPING WING SYSTEM DESIGN

Wing Morphology: Size and Weight

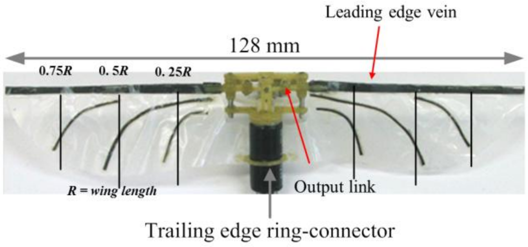
The original wing length from tip to tip is 128 mm. For our purpose, we scale up the length double its original size. However, we do not consider the weight of the flapping wing as this scale up model is for flow visualization in wind tunnel application.

Method to Attach Wing to Flapper

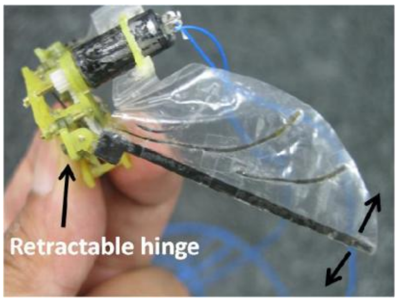
The wings were directly connected to the output links at the root of the leading edge veins. The trailing edges of the wings near wing roots were connected to installed motor as shown in Fig. 1 so that the wings can be twisted from wing root to wing tip during flapping motion.

Power Supply

The ornithopter system is actuated at 12 V by an external power supply (DC power supply) through very thin copper electric wires. At the applied voltage of 12 V, the flapping wing system could flap at the flapping frequency of about 37 Hz which is similar to the real beetle.



(a)



(b)

Fig. 1. A flapping wing system.

4. FLOW VISUALIZATION OF FLAPPING WING

In many of the air flow experiments, it is very helpful to have an appreciation of the flow pattern existing. Banerjee et all. conducted an experiment for a flapping wing in a water tank, of size (150 cm x 50cm x 75cm). Sodium fluorescent dye was used to trace the fluid path. The research was to visualize the vortex dominated flow in flapping flight by injecting dye at suitable positions over the wing (9). The amount of dye injected and the location of ejection was however based on hit and trial to get a good visualization. The frequency of the flapping wing set for the experiment was 0.46 Hz and 0.7 Hz (9).

Tethered flight experiments on the visualization of flow field around the flapping wing of a drone beetle were conducted in Eiffel type low speed wind tunnel by Kitagawa et. all (8). He showed that the beetle (*Anomala cuprea)* has four phases of wing motions namely, feathering, clap-and-fling, upstroke and downstroke phases (8).

A study was carried out to investigate the effects of the reduced frequency of a dragonfly-type model with two pairs of wings at low Reynolds numbers (12). It stated that the fore-wing and hind-wing of the model had a phase difference of 90°, and incidence angles of 0° and 10°, respectively (12).

4.1 Experimental Setup

The flow visualization of the wing wake region of the beetle-mimicking ornithopter was conducted by using a smoke-wire technique. The smoke flow visualization experiment was performed in a low speed wind tunnel.

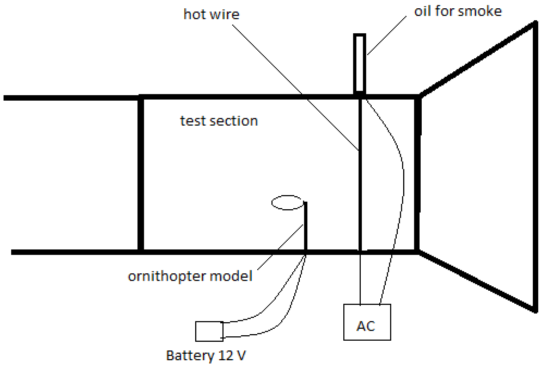


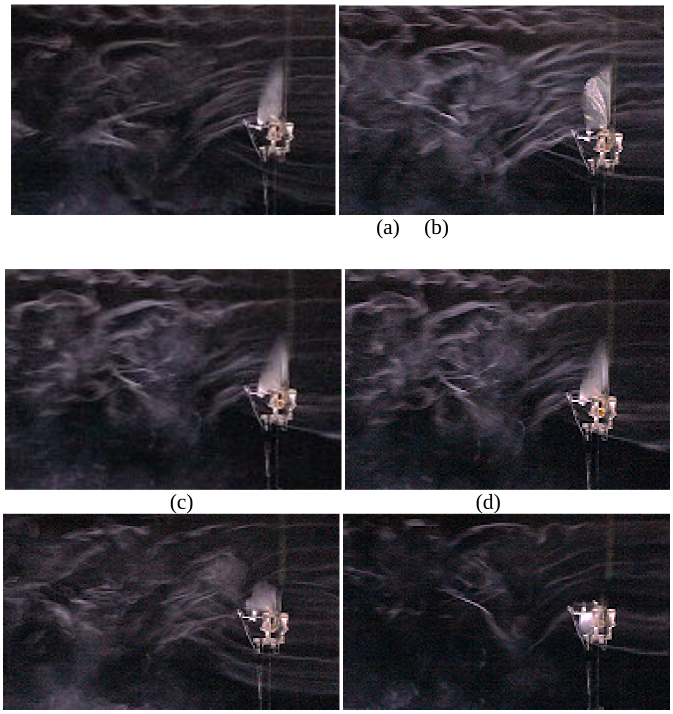
Fig. 2. Schematic diagram of experimental setup.

The low speed wind tunnel has a test section of 300 mm x 300 mm x 600 mm. The hot wire was made up from two interwoven guitar strings which were attached to a supply voltage at both ends. The liquid used to generate the smoke in this experiment was SAFEX oil. After calibration of the wind tunnel, the experiment was setup as in Fig.2.The velocity of the wind tunnel was set to 10 m/s. The proper voltage supplied for the hot wire was 11 V. At this voltage, the smoke generated by the hot wire was steady and uniform.

The ornithopter was supplied a voltage of 12 V with frequency of 37 Hz. The model was positioned at 0° angle of attack. A camera was put in front of the test section to capture the image of the flow. The camera can capture the image at 25 frames per second.

5. RESULT

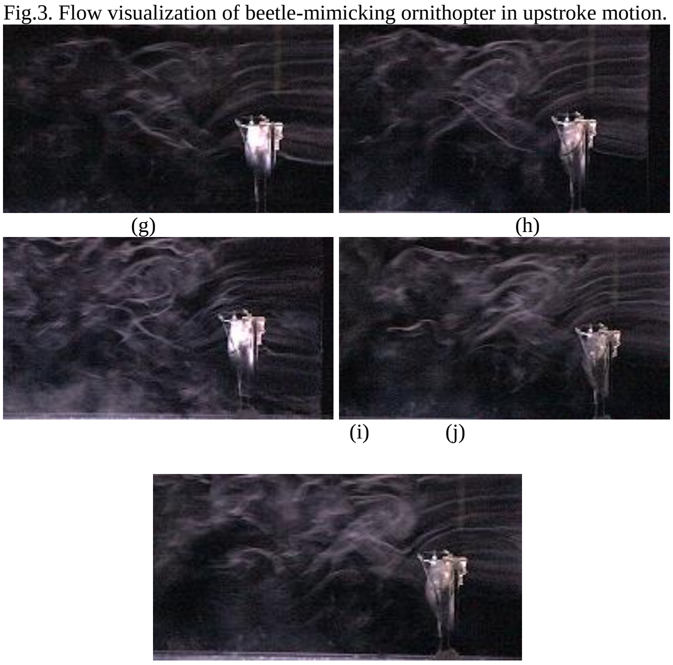
Fig. 3 (a)-(f) showed the upstroke phase of the motion. Meanwhile Fig. 4 (g)-(k) showed the downstroke motion. Due to lacking of high speed camera, the images captured were not of the top quality. However, in the images, we can see that there are significant vortices created during the flapping which contributed to the lift upwards. As the study is preliminary to show the existence of vortices in the beetle-mimicking ornithopter, it is sufficient to see the generation of vortices around the wing. From the pictures, it can be seen that more vortices are generated when the wing tip is at the highest point during upstroke phase. In addition, even more vortices are created at the lowest point during the downstroke phase. Fejtek and Nehera (1980) showed that maximum lift and thrust were produced during the down stroke motion of the flapping wing.


(a) (b)

(c) (d)

(e) (f)

Fig.3. Flow visualization of beetle-mimicking ornithopter in upstroke motion.


(g) (h)

(i) (j)

(k)

Fig. 4. Flow visualization of beetle-mimicking ornithopter in downstroke motion.

In (12), it mentioned that the streaklines on the upper surface of the model wing were attached to the wing surface while the streaklines on the lower surface of the model wing were bent in the upstroke direction during the upstroke wing motion. Fig. 3(a) and 3(e) depict this situation. However, the streakline on the upper surface bent in the downstroke direction while the streakline on the lower surface attached to the wing surface during the downstroke wing motion (12). Fig. 4(h) and 4(k) portray the situation clearly.

6. CONCLUSION AND FUTURE WORKS

In this work, we attempted to scale up a beetle mimicking ornithopter doubles the original size of an established model developed by Konkuk University. The flapping wing system of the beetle developed can flap its wings at a frequency of 37 Hz with a designated flapping angle of 160° which are comparable to those of the real beetle. The trailing edges of the wings near wing roots were connected to the installed motor so that the wings can be twisted from root to tip during the flapping motion.

This model is used in low speed wind tunnel testing. Flow visualization experiments was carried out. Due to the equipment used to capture the image is an ordinary camera with speed of 25 frames per second, the photos taken are not up to the best of quality. However, the images showed the existence of vortices in the flow. For future works, a high speed camera can be used with 2000 – 5000 frames per seconds to capture the image appropriately and accurately. For numerical simulation, the effort will be extended into next step of work.The data from wind tunnel testing will be used as initial and guessing values for modeling the ornithopter.

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