Experimental and Computational Investigation of Aerodynamic Characteristics of Hovering Coleoptera

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Abstract

Aerodynamic characteristics of Coleoptera species of Epilachna quadricollis and Allomyrina dichotoma are experimentally and numerically investigated. Using digital high speed camera and smoke wire technique, we visualized the continuous wing kinematics and the flight motion of free-flying coleoptera. The experimental visualization shows that the elytra flapped concurrently with the main wing both in the downstroke and upstroke motions. The wing motion of Epilachna quadricollis was captured and analyzed frame by frame to identify the kinematics of the wings and to implement it in the movement of a model wing (thin plate) in the simulation. The two-dimensional simulation of Epilachna quadricollis hovering flight was performed by assuming the wing cross section shape as a thin plate, even though most of insect's wings are made of curved corrugated membrane. The effect of Reynolds number are investigated by the simulation. Meanwhile, in order to investigate the role and effect of elytra, the flow visualization of Allomyrina dichotoma was carried on using smoke wire visualization technique. Here, we confirmed that the vortex generated by elytra due to its movement is strongly influence the vortex dynamic generated by hind wings.

1. Introduction

The recent study on insect flight and the understanding how flapping mechanism can demonstrate an outstanding aerodynamic performance has become an issue for about more than century, but has remained unsolved. Even nowadays, researchers were unable to accurately quantify the complex wing kinematics of flapping insects or measure the forces and flows around their wings. However, recent visualization tools, computational simulation, and developments of mechanical modeling have allowed researchers to formulate basic understanding of flapping mechanism. These mechanical and computational fluid dynamic models, as well as flow visualization techniques, have revealed that the flow characteristics of flapping flight are different from those of non-flapping.

Understanding of how flow field around the wings formed due to flapping motion was started by observations of tethered flying insects in the wind tunnel. The smoke visualization technique in the wind tunnel could examine and observe the vortices generated by the insect's wings. These visualization technique was combined with detailed analyses of wing kinematics, might provide a basis for evaluating theories about the aerodynamics of insect flight. However, it is extremely difficult to obtain repeatable airflow data using live insects, due to their small size, as well as handling those live insects it self. Researchers have overcome these limitations using two strategies. The first method involves constructing dynamically scaled models on which it is easier to directly measure aerodynamic forces and visualize flow characteristics, and second approach is to construct computational fluid dynamic simulations of flapping wings.

Ellington et al. [1-3] published a report, showing that the insect wing supports a particular type of vortex, namely the leading-edge vortex. This vortex is stable during the wing's downstroke and revealed that the leading-edge vortex has a helical flow shape, and perhaps this phenomenon could explain how flapping mechanism can generate surprisingly large lift forces. The authors were able to describe such kind of phenomenon in detail, due to the size of mechanical model of wing it self is quite big with over a meter in span wise direction, which allowed repeatable observations. Dickinson et al. [4] proposed that the enhanced aerodynamic performance of insects results from an interaction of three mechanisms: delayed stall, rotational circulation, and wake capture. They

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constructed dynamically scaled model of fruitfly (*Drosophila Melanogaster*) and published an excellent paper showing quantitative velocity vector data using digital particle image velocimetry technique (DPIV) with their dynamically scaled model (robofly) [4-7].

The interest of insect flight study has been not only motivated by the explanation and understanding the theory of flapping mechanism and its outstanding aerodynamic performance, but also by the purpose of constructing unmanned air vehicle based on flapping wing mechanism instead of conventional fixed-wing, which is more efficient and useful to operate in highly extreme environment condition such as mars exploration mission. The insect species such as dragonfly, fruitfly, butterfly, and howkmoth are widely used as a typical model of insect species used both in the computational simulation, dynamic mechanical model, or even as a live test object in the wind tunnel. However, no investigation has been performed to simulate *coleoptera* flight motion. As one of insect species which has a pair of wings, coleoptera has a unique wings configuration compared to other pair-wings configuration insects. Unlike dragonfly, cicada, or butterfly whose wing formed a front and rear wing configuration, coleoptera hind wings are folded and covered by elytra. While coleoptera starts to stroke their wings, the elytra are opened and the hind wings are unfolded. The vortex generated by the movement of elytra should make some influences to the vortices generated by the wings in some ways. The flow visualization technique has been greatly helped us to examine such kind of phenomenon, even though it is quite tough to handle and work with live insects, we tried to describe the physical phenomenon and explore our understanding about the role of elytra and its effect to the coleoptera flight performance in terms of aerdynamics point of view. In this paper, the flight motion of the *coleoptera* was computationally simulated

2. Material and Method

2.1 Experimental Method

Experimental visualization using digital high speed camera (Photron APX) was conducted to observe the flapping kinematics of Coleoptera both in hovering and forward flight. The coleopteran (*Epilachna quadricollis*) was release into an enclosed flight cube chamber made from transparent acrylics. One high speed camera was orthogonally aligned and located outside the acryl box, while halogen lamp was used as a light source. The Coleoptera's wing motion was imaged with high-speed camera at 2000 frames per second in 1μs shutter time and 1024x1024 pixels screen resolution. In this experiment, we captured the continuous wing motions of Coleoptera and recorded the coordinate and pitch angle data of wing displacement. The general experiment set-up and apparatus are shown in fig. 1.

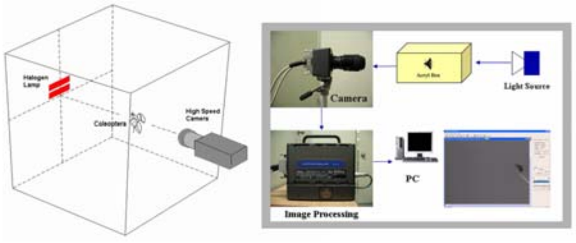

Fig. 1 Experimental apparatus setup

The continuous wing kinematics of *Epilachna quadricollis* was captured during hovering and forward flight. Experimental visualization shows that he main wing and the elytra flap concurrently in the same phase of downstroke and upstroke motion. For for hovering flight for one stroke phase there are 16 frame images, which mean the flapping period can be simply calculated by 16 x 1/2000s = 0.008 second (1 frame image is 1/2000 second). Therefore the flapping frequency can be calculated f = 1/T = 125 Hz.

With the body length around 5 mm and wing chord 2 mm, coleoptera (Epilachna quadricollis) flapped their wings with the stroke plane inclined around 10 degree from horizontal coordinate, which can be classified as normal hovering type. The stroke plane has length around 4.5 times its chord length, which means that the average speed of the wing during flapping is around 2.25 m/s. This wing speed is used to define the Reynolds number in the hovering motion in this study. Using photron fastcam viewer software, sequential movement pictures of wing were captured as shown in fig. 2a. From those sequential pictures, the displacement of wing cross section was measured. The mid span of wing cross section was chosen to simplify the complex wing shape due to its flexibility during the flapping motion. These measured coordinate was used in order to define wing kinematics of coleoptera

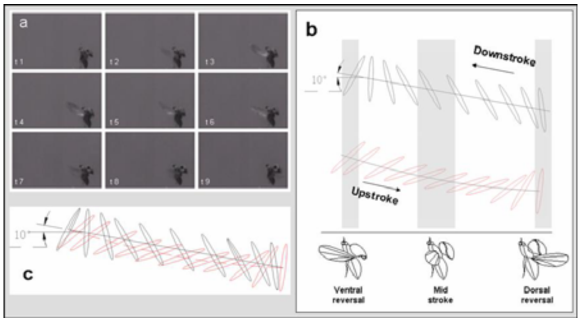

Fig. 2 a) Sequential movement of wings motion during hovering flight. b) Coleoptera wing kinematics during hovering flight. downstroke (black line) and upstroke (red line) motion

2.2 Numerical Method

Computational simulation was performed to investigate the flow characteristics and vortices structure around the Coleoptera's wings using CFD commercial software ADINA (ADINA R&D, Inc.) based on finite element method (FEM). The wing was modeled as a simple 2-D model and used the kinematics motion obtained from the experiment. The governing equation of the flow are described by the two dimensional unsteady incompressible Navier-Stokes equations as follows

$$\frac{\partial \rho}{\partial t} + U \cdot \nabla \rho + \rho \nabla \cdot U = 0 \tag{1}$$

$$\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u - \nabla \cdot \tau = f_x^B \tag{2a}$$

$$\rho \frac{\partial v}{\partial t} + \rho v \cdot \nabla v - \nabla \cdot \tau = f_y^B \tag{2b}$$

where t is the time, ρ is the density, U is velocity resultant, while u and v is the velocity vector in x and y, respectively, f^B is the body force vector of the fluid medium, and τ is the stress tensor

2.3 Flow Visualization

In order to investigate the role and effect of elytra, the flow visualization of *Allomyrina dichotoma* was carried on using smoke wire visualization technique. Due to its small size, we didn't use *Epilachna quadricollis* for flow visualization. Even though the size between them is quite different, however from the kinematics analysis obtain from visualization using high speed camera, both insects species have quite similar wings kinematics. Our main objective in this part is to build our understanding and explore the role of elytra. We assume that the flows formed by those two insects are quite comparable, so that the effect and the role of elytra can be explained.

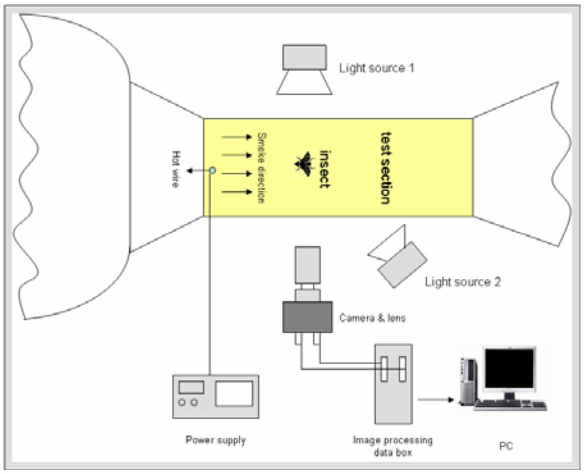

Fig. 3 Smoke wire visualization technique apparatus setup

Using high speed camera (Photron APX) we investigate both the wing kinematics of insects and flow characteristics around the wings. The insect's wing motion was imaged with high-speed camera at 2000 frames per second in 1μs shutter time and 1024x1024 pixels screen resolution. In this experiment, the continuous wing motions of insect were captured during flapping (downstroke and upstroke motion) as well as the vortex shedding generated by the insect's wing. Figure 3 presents the experimental apparatus setup for smoke wire visualization. The insect is placed inside the test section of a wind tunnel that surrounded by transparent-wall, and a hot wire is stretched in front of the device. The smoke is produced by sticking the liquid paraffin onto the wire that is connected to a DC power supply. During the test, the wind tunnel is operated at 0.5 to 1 m/s of wind speed to blow the laminar-flow of smoke over the flapping device. A high speed camera (Photron FASTCAM, Ultima APX®) is operated at 2000 fps (frame per second) for capturing the images of the generated vortex over the flapping wing. A personal computer with the installed photron fastcam viewer software[R] inside is connected to the image-processing-unit of the camera for recording the captured images and controlling the camera. Figure 7 presents the top and side view of closed subsonic wind tunnel used in the experiment, whose test section size i s 1m(W)×1m(H)×3m(L). This subsonic wind tunnel one of facilities in aerodynamics design laboratory at Konkuk University.

3. Results and Discussion

3.1 Epilachna quadricollis hovering flight

Computational simulation was conducted to investigate the flow characteristics and vortices structure around the coleoptera's wings using CFD commercial software ADINA [R]. The wing was modeled as a simple 2-D model. For simplification, at the first stage, simulation only focused to the main wing in the hovering flight (without elytra). The simulation was performed in laminar-incompressible-unsteady flow in the Reynolds number (Re) of 450. The wing cross section shape was assumed as thin plate. Because the mean chord of Coleoptera's wing was around 2mm, length of the thin plate was 2 mm, and the thickness was 5% of the length.

Figure 4 shows stream function and vortices during flapping motion at 0.25t/T, 0.5t/T, 0.75t/T and 0,95t/T. At the beginning of downstroke, both the leading edge and trailing edge vortex was shed, and as time goes by, both leading edge and trailing edge vortex become detached at the final stage of downstroke motion, and when the wing strats to rotate the trailing edge vortex which is detached before is located at the bottom of wing and keep staying until the middle of upstroke phase. Unlike the downstroke motion, the leading edge and trailing edge vortex start to detach from the beginning of upstroke motion.

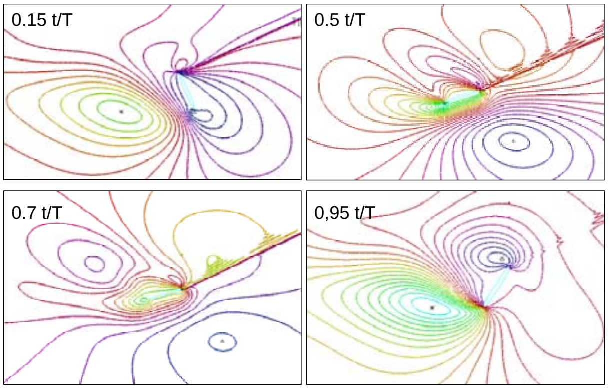

Fig. 4 Smoke wire visualization technique apparatus setup

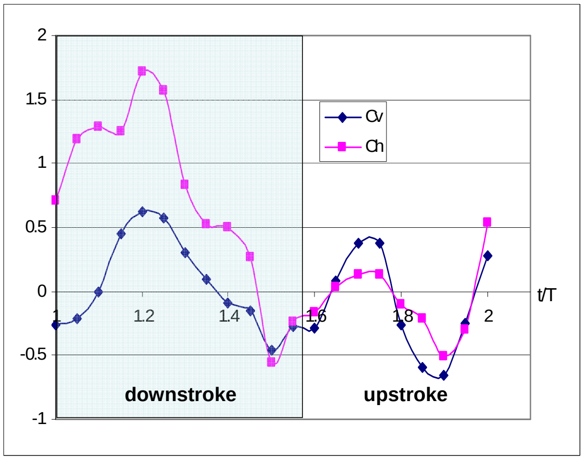

Fig. 5 Smoke wire visualization technique apparatus setup

Figure 5 shows the local vertical and horizontal forces coefficient calculated from the numerical simulation. The vertical and horizontal force was generated and increased while the leading edge and trailing edge vortex are still attached, and then decrease as leading edge and trailing edge vortex become detached from the wing and the angle of attack increasing as the wing starts to rotate. From these results it also can be seen that vertical force generated by the wing to counter the body weight during hovering motion continuously produced at both downstroke and upstroke motion. Meanwhile the horizontal force generated by the wing is mostly comes from the downstroke motion.

3.2 Vortex shedding visualization of Allomyrina dichotoma

Figure 6 A through D present the flow visualization of coleoptera during upstroke motion. While the vortex shed by the wings at the beginning of upstroke motion, the elytra are also generating the vortex. Those vortices are going backward and its direction is a little bit down due to the elytra are also in the upstroke motion phase and move up. From the smoke generated in the wind tunnel, it can be seen that those vortices is pushing the vortices generated by the wings, so that its make the vortices generated by the wings keep in the bottom of the coleoptera body even until the end of upstroke motion and the wings start to rotate. When the wings are in the clip and fling position (start to begin the downstroke motion), the vortices generated by the wings at the upstroke motion start to move backward (fig. 6 E and F). Meanwhile the wings start to generate vortex, the elytra also generate the vortex. Unlike the upstroke case, those vortices are pushing the wing's vortices, so that it moves backward faster than the vortices that are still in the bottom of body (generated at the upstroke motion) and finally both vortices reach the same horizontal position (fig. 6 G through J).

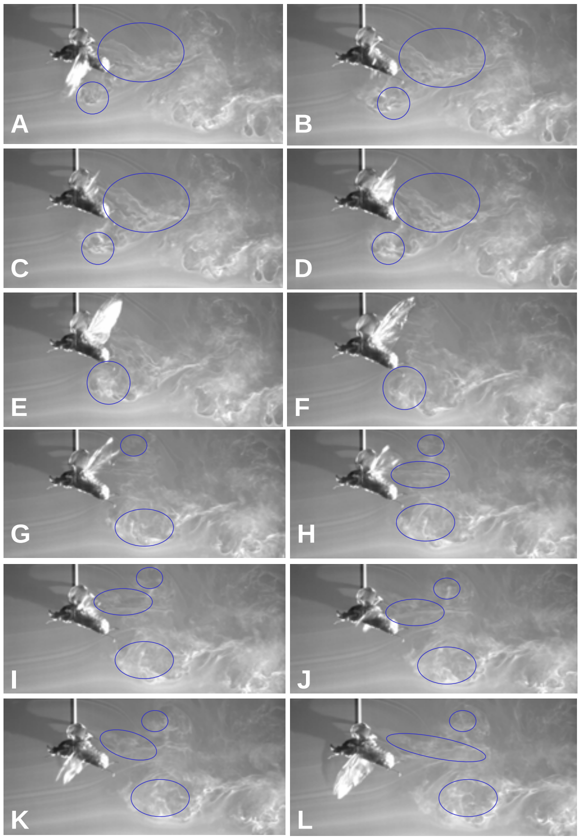

Fig. 6 Smoke wire visualization technique apparatus setup

Acknowledgement

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