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Short Paper

Visualization of Three-Dimensional Vortex Structures around a Dragonfly with Dynamic PIV

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1. Introduction

The purpose of this investigation is to clarify the generation mechanism for the aerodynamic force from the flapping wings of insects. Since insects use a low-Reynolds number effect and changing flow properties, the insects' flight is different from the flight of man-made airplane wings. Azuma A. et al. (1984) showed that the feathering angle is important in generating a vertical force with a flapping wing. However, the relationship between the vorticity field and the aerodynamic force was not clear. Adrian et al. (2004) showed flow field around a dragonfly with smoke-wire method. The result showed the simple U-shaped separation occurs in flow around a dragonfly. The U-shaped separation is one of the simplest analytical solutions of the Navier-Stokes equation in dynamic stall flow over a wing. In this investigation, a quantitative analysis of vortex structure around a dragonfly and a time varying vertical force were measured directly using a dynamic PIV and a micro-load cell system. The experimental results showed that the continuous vortex tubes were observed such as the U-shaped separation. Moreover, these vortex tubes play an important role in the aerodynamic force generated by the flapping wings of insects.

2. Experimental Setup

Figure 1 shows a micro-road cell system for insect flight measurements. Since the aerodynamic force for dragonflies is only in the neighborhood of 10 mN, but the frequency of the flapping motion is very high (about 30 Hz), a light-weight and high-stiffness cantilever is required. In this system, the cantilever was fabricated from carbon fiber to achieve light weight and high stiffness. The resonance frequency of the system was 66 Hz, which is about two times larger than the flapping frequency of the dragonfly. The error in this system is less than 1 %, and the available range of measurement is from 0.981 mN to 49.1 mN. In order to measure an instantaneous vorticity field in two dimensions we used a dynamic PIV system (X-Stream VISION™ : IDT Co., Ltd.). The resolution of this system is 512 pixel × 512 pixel and the sampling frequency is 4 kHz. The instantaneous flow field was measured at several intervals from the root to the tip of the wing. Each data point was reconstructed into the three dimensional field at the same phase as the reference signal that was obtained by the high speed camera. To simplify the experiment, we removed hindwings and studied only the forewings of the dragonflies.

3. Results and Discussion

Since the flow angles are changed during one cycle of the flapping motion, the direction of lifting force act on the wings are also changed. Aerodynamic force of vertical direction of the dragonfly was measured as shown in Fig. 2. The vertical force of F was normalized by the weight of the dragonfly, W. The horizontal axis shows the phase angle (θ) of the flapping motion. The top dead center and bottom dead center is defined to 0 and 180 degrees, respectively. The maximum lift was obtained in the downstroke (θ= 0 to 180 degrees) at phase angle of 110 degrees. In the upstroke (θ= 180 to 360 degrees), the vertical force was negative, but its absolute value was smaller than that of the downstroke. The average value of vertical force generated by the forewings was equal to 0.6 times of the weight of the dragonfly. Here, we should take note of the vertical force generated by the two pairs of wings was 1.2 times larger than the dragonfly's weight, which was enough for level flight.

Figure 3 shows the iso-surface of the phase averaged vorticity around the flapping wing of the dragonfly. The blue and the red surface indicate the negative and positive vorticity shed from the flapping wing, respectively. When the maximum lift was generated at the phase angle of 110 degree, strong vortices were generated by separated flow from the leading-edge as shown in Fig. 3(a). The continuous vortices such as the tube vortices were observed on the upper surface of the wing in the downstroke, which seems to be the part of the U-shaped separation. Moreover, the diameter of the tube was almost same as the chord length of the wing. This structure is in good agreement with the flow pattern visualized by Adrian et al. (2004). Although the flapping wings produce the three-dimensional velocity distributions on the wings, unsteady, dynamic stall flow over a high aspect-ratio wing such as the dragonflies makes U-shape separation which is entirely consistent with the solution of the N-S equations. As a result, the topology of the separated flow is almost two dimensional without near the wing-tip. Since the negative pressure act on the wing surface from the root to the tip with tube vortices, it generates aerodynamic force effectively. Therefore, the vertical force during the downstroke is large. The strong vortex was also observed in the upstroke. But it distributed under the wing surface. Moreover, the vortices had three-dimensional structures. These vortices do not generate lift, but they do generate thrust force (Yang, C. J. and Lee, Y. H., (2006); Chang, J. W. and Sohn, M. H., (2006)).

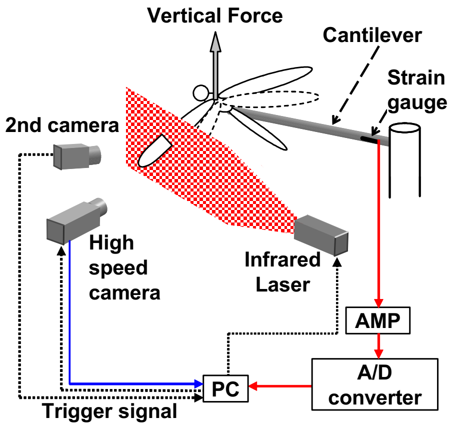


Fig. 1. Schematics of micro-load cell and dynamic PIV for insects' flight measurement.

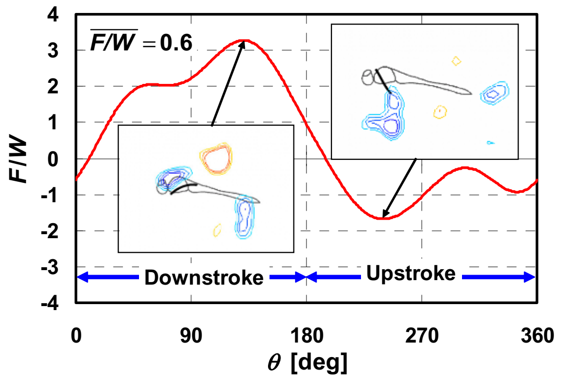
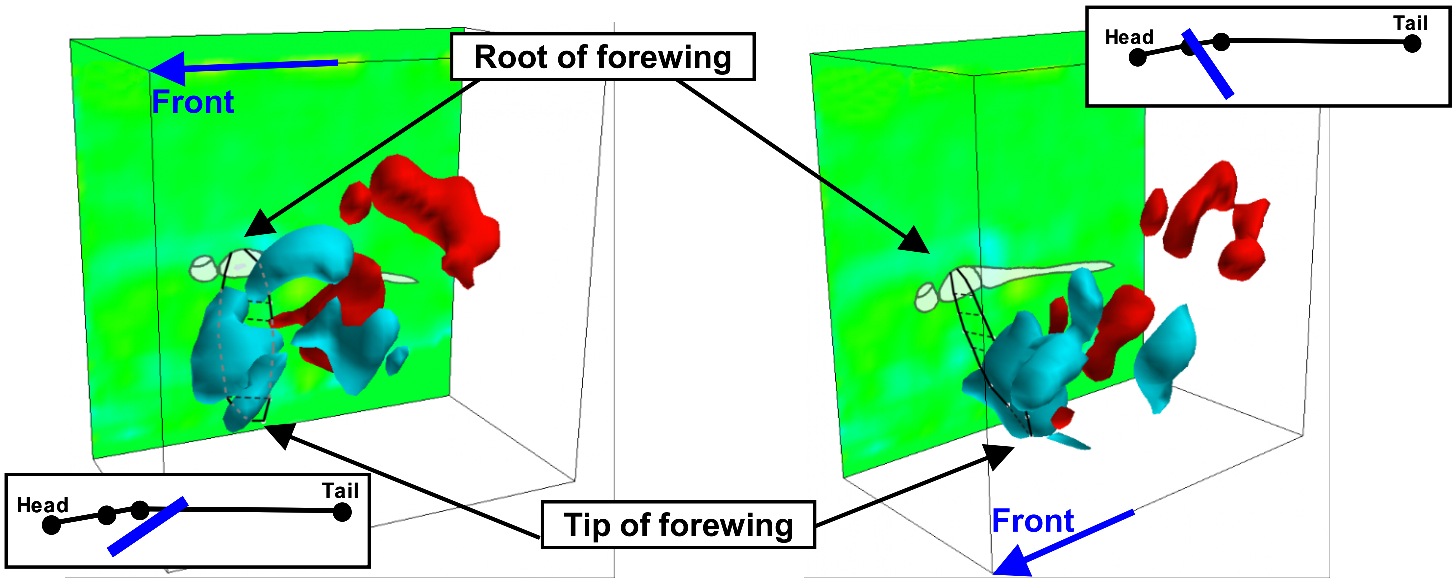


Fig. 2. Aerodynamic vertical force evolution against phase angle of flapping motion.



(a) Maximum lift (b) Minimum lift

Fig. 3. Three-dimensional vortex structures around the flapping wing ($\varphi / f = \pm 5$).

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