Dynamic Behaviors of a Vortex Ring on a Butterfly and a Small Flapping Robot

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ABSTRACT

Butterflies fly combining wing flapping and gliding efficiently and have beautiful flight patterns. Micro-Air-Vehicles (MAVs) and micro-flight robots that mimic the flight mechanisms of insects have been attracting significant attention in recent years. A number of MAVs and micro-flight robots that use various devices have been reported. However, these robots were not practical. A number of studies on the mechanism of butterfly flight have been carried out. Moreover, a number of recent studies have examined the flow field around an insect wing, such as a leading edge vortex (LEV) structure using the first digital particle image velocimetry (DPIV). We have carried out the PIV measurement around a butterfly wing and have visualized a vortex ring formed on the wing clearly. On the other hand, we developed a small flapping robot without tail wings, which is similar to the butterfly. The purpose of the present study is to clarify the dynamic behaviors of the vortex rings formed on the wings of the butterfly and the small flapping robot. A vortex ring is formed over the wings of the butterfly and small flapping robot with stable flight when the wings flap downward. An another vortex ring is formed below the butterfly wings when the wings flap upward and it was smaller than that in downward flapping motion because of the elastic deformation of the wings. Both vortex rings pass through the butterfly completely at the top and bottom dead position in the flapping motion.

1 INTRODUCTION

Micro-air-vehicles (MAVs) and micro-flight robots have been actively developed in recent years. These technologies are being developed for use in search and rescue operations in areas witt a high risk of secondary disasters and for monitoring security risks. Several MAVs and micro-flight robots that employ various devices have been reported. Among them, flapping robots that mimic the flight mechanism of insects and that have good flying abilities have been attracting considerable attention [1][2]. Tanaka et al. [3][4] developed a very small and lightweight butterfly-type ornithopter (BTO) to investigate butterfly flight. Their BTO has a mass of 0.4 g, a wingspan of 140 mm, and a flapping frequency of 10 Hz. However, these robots require a tail wing to achieve stable flight. It is difficult to develop flapping robots that do not have a tail wing like butterflies. One reason for this is that the flying mechanism of insects has not yet been sufficiently clarified.

Several recent studies have investigated the mechanism of butterfly flight [5][6]. Dickinson et al. [7] identified three important motions; delayed stall, rotational circulation, and wake capture. Senda et al. [8] analyzed these motions and measured the forces of the butterfly *Parantica sita* by observing its flight.

Several studies have examined the flow field around an insect wing [9]. Michael et al. [10] used flow visualization and instantaneous force measurements of tethered fruit flies, *Drosophila melanogaster*, to study the dynamics of force generation during flight. They presented a reconstruction of a vortex loop during the downstroke and ventral flip. Richard et al. [11] used first digital particle image velocimetry (DPIV) to investigate flow around the wings of an insect. They investigate the moth *Manduca sexta* and reported the relationship between the structure of the leading edge vortex (LEV) and force production. They [12] employed smoke visualization techniques to analyze the aerodynamic mechanisms of free-flying bumblebees and reported the independent LEVs on both wings. However, the dynamic behavior of the vortex that forms on the insect wing and its growth process have not been clarified.

By observing the flight of the butterfly *Cynthia cardui* we have clarified the behavior of its wings in flight. By spatial evaluation of the wing during flapping flight, we found that the flapping angle, lead-lag angle and feathering angle of the butterfly are periodic. Moreover, we have clarified that the wing deforms elastically in both the wing span and chord directions [13]. Based on these results, we developed a small flapping robot that does not have tail wings and hence resembles a real butterfly [14]. We found that elastic deformations of the wing cause twisting motions of the wing, which enable stable flight [15]. Moreover, we performed particle image velocity (PIV) measurements around a butterfly wing and clearly visualized a vortex ring formed on the wing; this vortex ring was formed over the wings for all the butterfly species examined [16]. However, the dynamic behavior of the vortex ring is not sufficiently well understood. We are particularly interested in the dynamic behavior of the vortex ring during up and down flapping.

The purpose of the present study is to clarify the dynamic behavior of the vortex rings that form above the wings of the butterfly and the small flapping robot. We performed PIV measurement around the wings and investigated the dynamic behavior of the vortex rings in upward and downward flapping motions.

2 EXPERIMENTAL SYSTEMS

2.1 Butterfly and small flapping robot

Figure 1(a) and (b) respectively depict the butterfly and small flapping robot used in the present study. Table 1 lists

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(a) Butterfly, *Idea leuconoe*

(b) Small Flapping robot

Figure 1: Butterfly and small flapping robot in our study

Table 1: Dimensions of butterfly and small flapping robot

	Butterfly	Small flapping robot
c [mm]	60	80
l [mm]	140	240
AR	2.3	3.0
m [g]	0.4	1.9
W/S [N/m^2]	0.6	1.5
f [Hz]	6	10

their wing chord length c, wing span length l, aspect ratio of the wing AR, mass m, wing load w/s, and flapping frequency of the wing f.

The butterfly shown Fig. 1(a) is *Idea leuconoe*; it was captured on our campus. The small flapping robot has a motor and battery and it weights approximately 1.9g. A crank mechanism is used to convert the rotary motion of the motor into flapping motion of the two wings with a flapping frequency of about 10 Hz. The battery can power flight for about 20 minutes. Over the time, the flapping frequency decreases to 9 Hz due to the voltage drop of the battery.

Figure 2 shows flight trajectories of the small flapping robot. The flying trajectories were recorded using a fixed digital video camera with a frame rate of 30 [fps]. The time when the flapping robot leaves the hand is taken to be t = 0.0

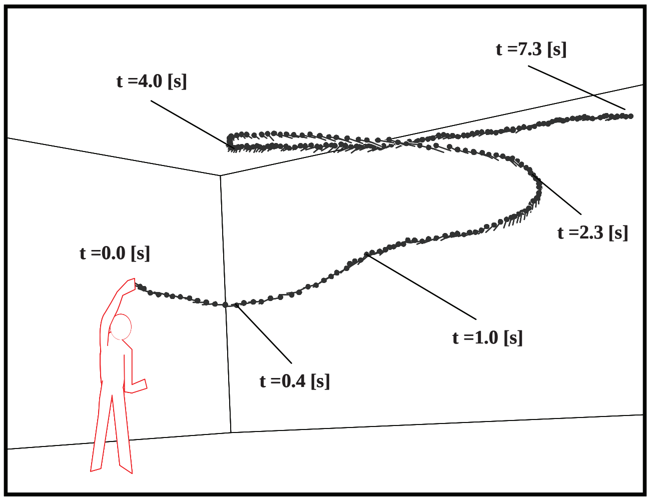


Figure 2: Flight trajectories of our small flapping robot

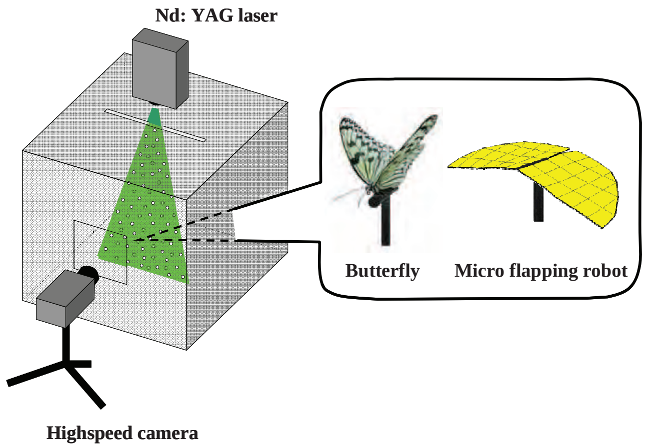


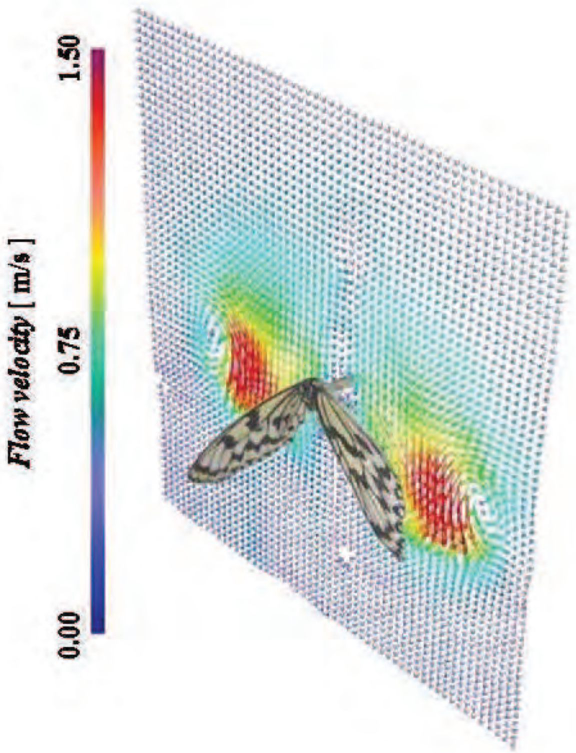
Figure 3: PIV measurement system in our study

[s] and flight trajectories are depicted up tp t = 7.3 [s].

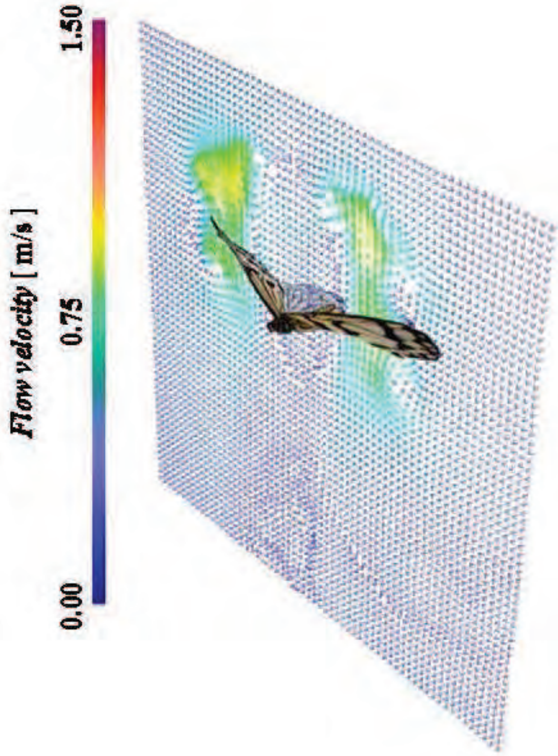
The flying posture of the small flapping robot becomes unstable and its height decreases from t = 0 to t = 0.4 [s]. The flying posture continues to be unstable until t = 1.0 [s], but the height of the robot increase. After t = 1.0 [s], the flying posture becomes almost constant and the robot ascends while performing large turns to the left. The small flapping robot flew stably for 20 minutes (i.e. for the life of the battery). The small flapping robot ascends for 7-8 minutes while slewing and then descends while slewing. This is because the revolution speeds of the motor decreases with decreasing voltage of the battery and consequently the flapping frequency generated by the crank mechanism decreases. By reversing the rotary motion of the motor applied to the crank mechanism, we found that the slewing direction in the flight of the small flapping robot is counterclockwise.

2.2 PIV measurement system

We performed PIV measurements using an acrylic container, a high-speed camera, a continuous-wave Nd:YAG laser, and a butterfly (see Fig. 3). The test section in the acrylic container is 900 [mm] long, 900 [mm] wide, and 900 [mm] deep. Expancel (Kanomax), which has a diameter of approximately 10 [m] and a specific gravity of 0.7, was used as tracer particles. In the butterfly experiments, the legs

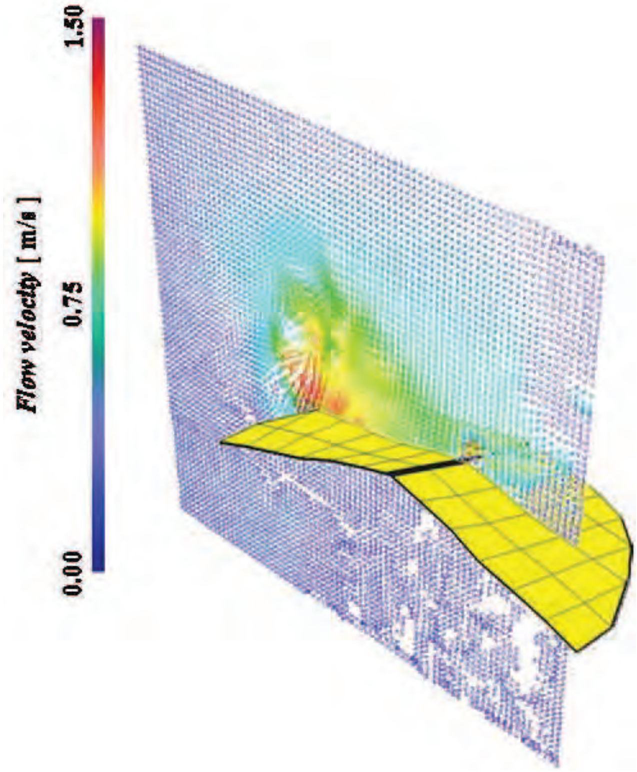


(a) Downward flapping motion

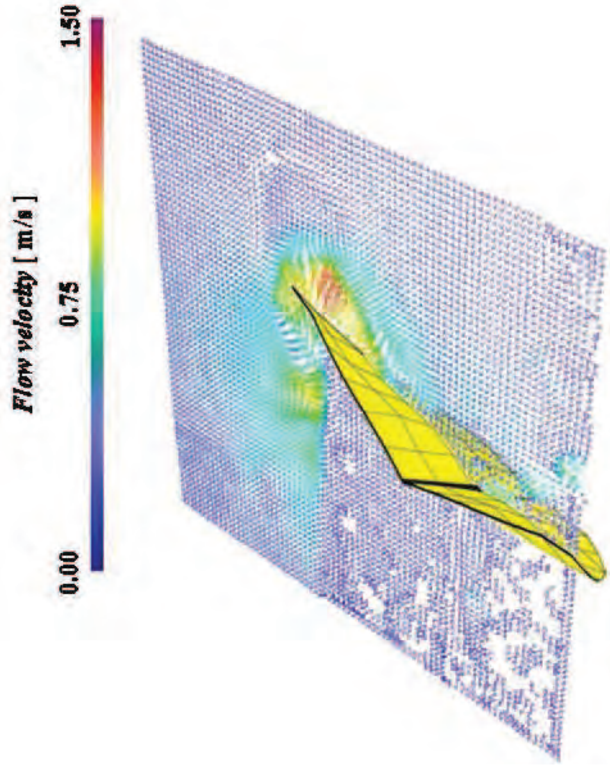


(b) Upward flapping motion

Figure 4: Velocity vectors around wings of the butterfly



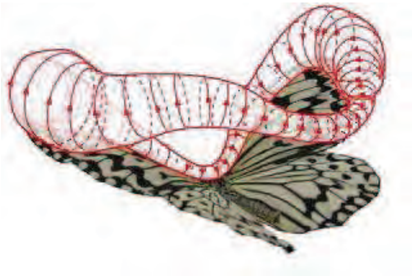
(a) Downward flapping motion



(b) Upward flapping motion

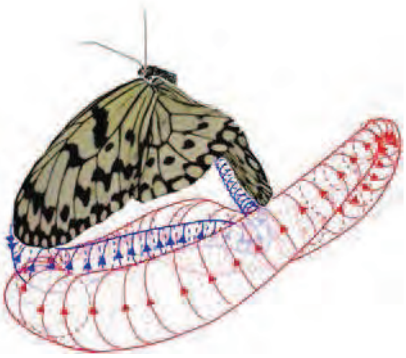
Figure 5: Velocity vectors around wings of the small flapping robot

of the butterfly were fixed to a shaft in the test section without hindering the butterfly's flight motion. In the small flapping robot experiments, the body of the robot was fixed to a shaft in the test section without hindering its flight motion and the flapping frequency was 10 Hz. Measurements were performed with the illumination plane aligned with the chord and with it aligned with the span. In the first configuration, 12 planes were studied at chordwise positions including the leading edge, the center of the wing chord, the trailing edge, and the wake. In the second configuration, four planes were studied at spanwise positions including the wing

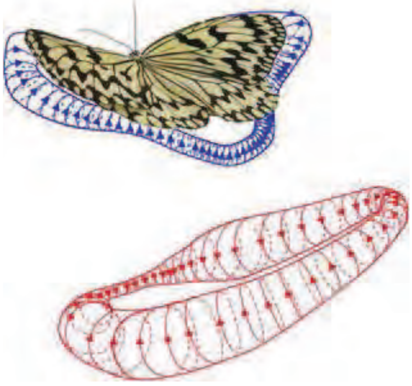


(a) Moving downward

(b) Moving further downward



(c) Moving upward



(d) Moving further upward

(e)Top dead position

Figure 6: Pattern diagrams of the vortex on the butterfly wings obtained by the PIV measurement results

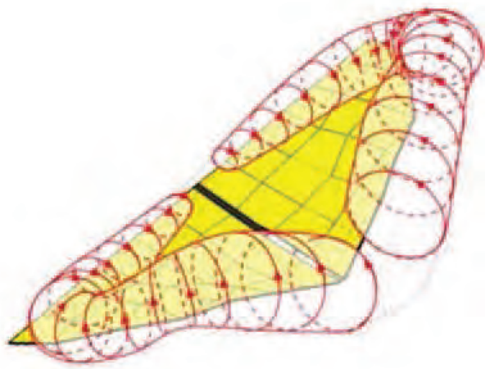


Figure 7: Pattern diagrams of the vortex on the wings of the small flapping robot obtained by the PIV measurement results

tip, the center of the chord, the basic point of the wing, and the body. Images were captured using a high-speed camera (2,000 [fps]) and the vortex flows that developed in the wing chord and span directions were investigated.

We investigated the wing tip traces of a fixed butterfly and found that the dynamic behavior of the wings was similar to that in take-off flight. Moreover, the dynamic behaviors of the butterfly wings and of the small flapping robot under fixed conditions are highly periodic. Therefore, the flow fields around the butterfly and small flapping robot are also expected to vary periodically. In the present study, we found a three-dimensional vortex above the wings by analyzing two-dimensional flow field at each point of the wings.

3 RESULTS AND DISCUSSIONS

3.1 Velocity vectors around wings of the butterfly and small flapping robot

Figures 4(a) and 4(b) respectively show velocity vectors around the butterfly wings with up and down flapping motion obtained by PIV measurements.

As the wings move downward (see Fig. 4(a)), a pair of vortices is clearly observed above the wings. This pair of vortices initially forms between the wings at the beginning of the downward flapping motion and then develops over the wing surfaces. Similarly, a pair of vortices is observed below the wing with upward flapping motion (see Fig. 4(b)). The size and velocity of vortices are smaller for downward flapping motion than for upward flapping motion. These vortices were observed at each point in the wing chord direction. That is, tube vortices form over the wings in the wing chord direction. Moreover, the tube vortices above the two wings are connected by one chord length. Furthermore, a LEV is observed in the wing span direction and it is connected with the tube vortices in the wing chord direction. As a result, a vortex ring formed over the wings of the butterfly [16].

Figures 5(a) and 5(b) respectively show velocity vectors around the wings of the small flapping robot with up and down flapping motion. Similarly to the butterfly, a pair of vortices is clearly observed above the wings of the robot (see Fig. 5(a)). Moreover, a pair of vortices is observed below the wings during upward flapping motion (see Fig. 5 (b)); this pair of vortices is smaller than those generated during downward flapping motion, which is the same as for the butterfly wing.

3.2 Dynamic behaviors of a vortex ring

Figure 6 shows pattern diagrams of the vortex on the butterfly wings obtained from vorticity isosurfaces which were derived by analyzing the PIV results for each point in the wing chord and span directions. Figures 6(a-e) show the results obtained for the region moving downward, moving further downward, moving upward, moving further upward and at the top dead position, respectively.

A vortex ring begins to form when the wings flap downward and it is completely formed over the wings when the wings flap downward to the bottom dead position (see Fig. 6(a)). The vortex ring develops over the wings when the wings flap further downward (see Fig. 6(b)) and then completely passes through the butterfly and grows until reaching the wake at the bottom dead position (see Fig. 6(c)). Another vortex ring begins to form when the wings flap upward (see Fig. 6(c)) and it is completely formed below the wings when the wings flap upward to the top dead position (see Fig. 6(d)). The vortex ring formed during upward flapping motion completely passes through the butterfly completely, just as during downward flapping (see Fig. 6(e)).

Both vortex rings completely pass through the butterfly at the top and bottom dead positions during the flapping motion. However, the size of the vortex ring that forms during downward flapping is larger than that formed during upward flapping. The veins in butterfly wings have different diameters on the upper and lower sides of the wings, which important butterfly wings with different elastic deformations during upward and downward flapping motions. Consequently, the vortex rings have different size and dynamic behaviors during upward and downward flapping and the lifts and drags generated differ accordingly. Butterflies are thought to generate lift and drag through the induced downward and backward flows in the vortex ring.

Figure 7 shows pattern diagrams obtained by PIV measurements for the vortex ring formed above the wings of the small flapping robot.

A vortex ring forms above the wings of the small flapping robot during stable flight, just as for butterfly wings. However, the vortex ring formed above the wing during unstable flight has a strange shape. Specifically, the rear of the vortex ring is deformed, making it difficult to form a vortex ring. It was found that the formation of a vortex ring above the wing is an important requisite for stable flight. However, we have not yet clarified the dynamic behaviors of the vortex ring of the small flapping robot.

4 CONCLUSIONS

A vortex ring was clearly observed above the wings of the butterfly and small flapping robot with stable flight. It was found that the formation of a vortex ring above the wing is an important requisite for stable flight.

Another vortex ring formed below the butterfly wings when the wings flap upward to the top dead position. This vortex was smaller than that formed during downward flapping due difference in the elastic deformation of the wings during upaward and downward flapping. Both vortex rings completely pass through the butterfly at the top and bottom dead positions during the flapping motion.

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