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A Study on the Wing Characteristics of Flies

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Abstract: This paper is concerned with the aerodynamic functions of fly wings. The free and tethered flight analyses were performed by using a digital high-speed video camera system. A liquid droplet impacting with a wing surface of fly was conducted to examine the wing characteristics. Microscopic observation of fly's wings were also conducted by using a laser beam microscope. The results of a series of observation and measurement revealed the flight characteristics of flies, such as the wing tip velocity, wing path, wing flexibility, wing structure, resistance to rain drops, and so forth.

Key words: Fluid mechanics, insect flight, flapping flight, fly wing, diptera, wing characteristics.

1. Introduction

Animal flight may be classified into gliding and flapping. Flapping flight is by far the most important mode of animal flight. On this planet, the first animal to acquire the capability of flight was the insects. Most adult insects have two pairs of wings, which arise as outgrowths of the cuticle from the second and third segments of the thorax. Flies possess a pair of wings, and they perform an extraordinary array of complex aerial manoeuvres. Dipteran flight has been a fascinating research subject for many years. Extensive investigations on the flight of flies have been conducted. The kinematics, dynamics, and control of the wing beat of tethered flying *Drosophila melanogaster* were investigated by using artificial slow motion pictures which were generated by single strobe flashes triggered in synchrony with the wing beat [1-3]. Recent studies on the aerodynamics of insect flight have begun to clarify the basic flow structure around the wings of the fly *Drosophila* [4-7]. The aero dynamics of insect flight for the purposes of the design of insect-like flapping wing micro air vehicles has also been discussed [8, 9]. In spite of many investigations, there still remains a wide unexplored domain. Research data on the wing characteristics of flies are insufficient.

In this paper, the wing beat and the drop wing tolerance of tethered fly were investigated by using slow motion pictures which were recorded by the high-speed video camera system. Free flight of a smaller fly was also investigated by the high-speed video camera system. Furthermore, the surface roughness of fly wings was measured by the optical shape measuring system. The wing characteristics of flies were revealed experimentally.

2. Experimental Apparatus and Procedures

In this study, three kinds of experiments were performed. At the beginning, beating behavior of flies was analyzed by using the high-speed video camera system. A schematic diagram of the experimental apparatus is shown in Fig. 1. The experimental system is composed of a high-speed video camera, a synchronization unit, a video cassette recorder, a video monitor, and a personal computer. In the tethered flight experiment, a live insect was stuck to a fishing line, and it was fixed to the stand as shown in Fig. 1. The beating behaviour of flies was recorded by the high-speed video

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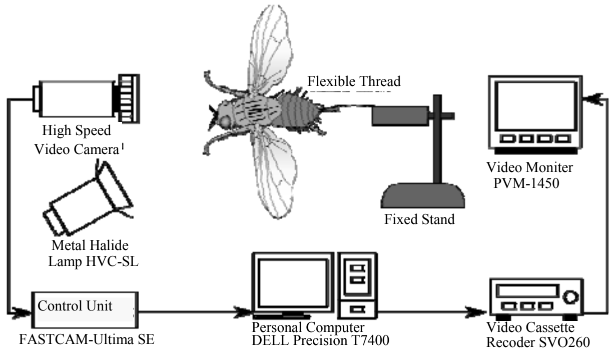

Fig. 1 Block diagram of experimental apparatus for beating analysis.

camera, and analyzed with the personal computer. The free flight experiment was also conducted by using smaller fly. In the free flight experiment, the fly was released from the small bottle by opening a lid. In the second place, the drop collision test on the wing of fly was performed. The water drop was dropped from the burette which was set in prescribed height. The impact of a water drop on the fly wing was observed with the high-speed video camera. In the third place, microscopic observation of the wing surface of flies was conducted by using a confocal laser scanning microscope. Measurement of the surface shape of wings is possible by this confocal laser scanning microscopy. The test wing was severed from the insect body before the measurement. Test flies were *Muscina stabulans* and *Drosphila hydei*. Test insects were collected in the field in Yurihonjo, Japan. The experiments were conducted under the room temperature in summer.

3. Experimental Results and Discussions

3.1 Wing Characteristics in Flapping Flight

Flies in tethered flapping flight were recorded at 13,500 frames per second to determine the motion of their wings. Fig. 2 shows a sequence of photographs showing the flapping behavior of tethered fly *Muscina stabulans*. The body length of test fly is L = 8.11 mm, and the wing length is l = 7.71 mm. The mean flapping frequency of the fly is $f_i \approx 154$ Hz. The wing surface is made taut to the maximum extent at the extreme of the upper stroke before the downstroke begins (t = 0). As it

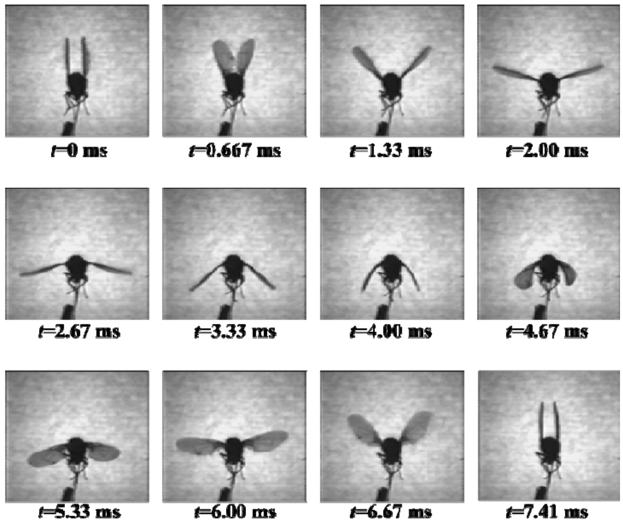

Fig. 2 The wingbeat of the tethered fly *Muscina stabulans*.

begins the leading edge deflects slightly downwards, whereas the trailing edges of the right and left wing approach each other (t = 0.67 ms). With an increased angle of attack, the flapping wing surface passes the horizontal and approaches the lowest point of the downstroke (t = 1.33-3.33 ms). As the muscles raise the wings contract, the wing tip part deflects downwards (t = 4.00-4.67 ms). This bending of the wings brings the effect of spring. The spring effect leads to the speedy recovery stroke of wings. Strain energy is released when the flapping motion changes into the recovery stroke. Strain energy is transformed into kinetic energy of the wing. Therefore, the time of the recovery stroke is slightly shorter than that of the downstroke (t = 4.00-7.41 ms). Fig. 3 shows the measurement result of the wingtip motion during flapping of the fly. The Cartesian coordinate system was chosen. It is orthogonal coordinate system, with the origin at the fly head, of the upper direction as the z coordinate axis, and the left wing direction as the y coordinate. The plots in Fig. 3 reveal the wingtip orbit of left wing flapping. In the upward arrow, the wings are ascending towards the top of the upstroke. It can be seen that the orbits of a power stroke and a recovery stroke during beating are different. The difference of the orbit of the power stroke and the recovery stroke shows the wing deflection. Fig. 4 shows the time variation of the magnitude of two dimensional velocities in the y-z plane.

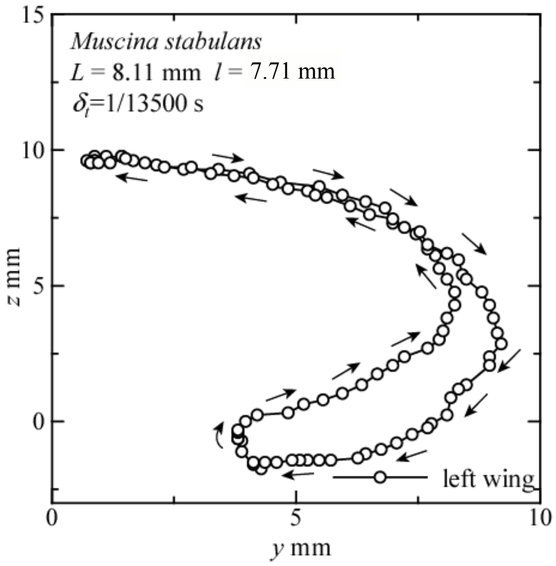

Fig. 3 Wingtip trajectory of fly flapping through one cycle.

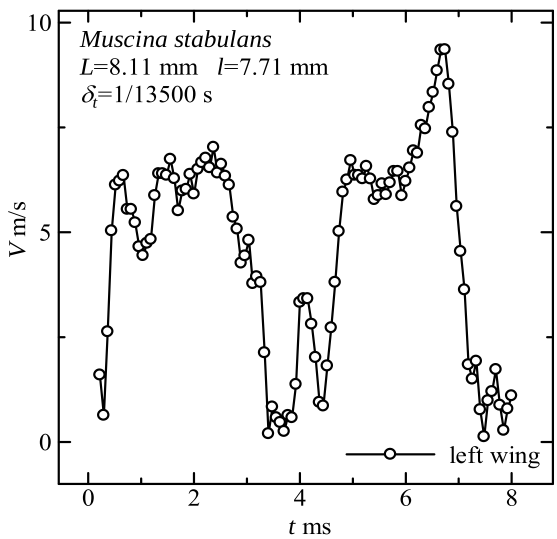

Fig. 4 Velocity variation of wingtip motion.

The velocity variation in Fig. 4 corresponds to about one period of wing flapping as shown in Fig. 2. The flapping wing surface is twisted throughout its ascent in Fig. 2 (t = 4.67-7.41 ms). The distal part of the wing does not deflect upwards throughout its descent. There is anisotropy in the elasticity of the fly wing. Such elastic characteristics described above are also observed in other flies. Fig. 5 shows the sequence for the free flight of a fly *Drosophila hydei* Sturtevant. In L = 2.96 mm, the wing length is l = 2.74 mm, the mass is m = 0.28 mg, and the wing beat frequency f_i = 282.7 Hz.

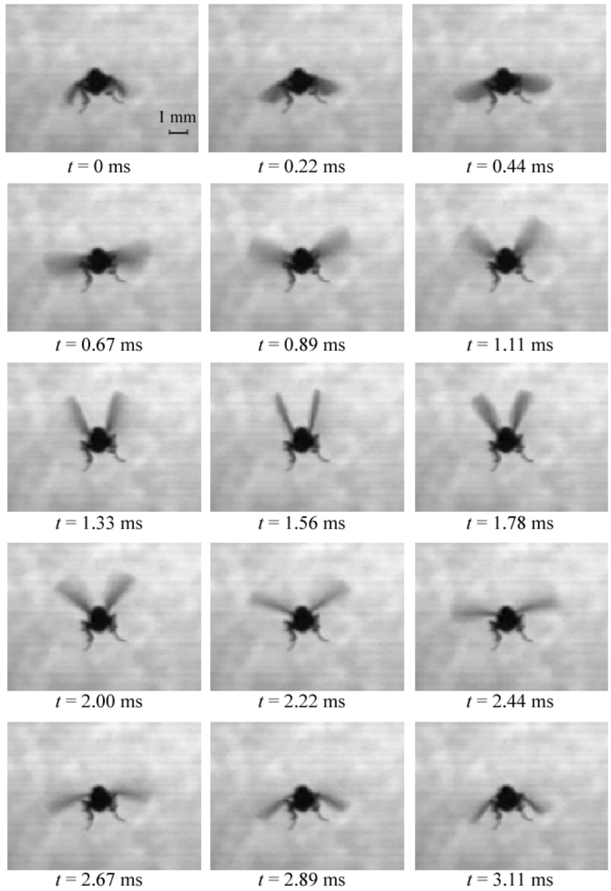

Fig. 5 Free flight of the fly *Drosophila hydei.*

3.2 Wing Characteristics in Droplet Collision

In this experiment, the drop collision test on the wing surface of fly was also performed to examine the tolerance to the raindrop. The single outstanding characteristics common to flies is the presence of only one pair of wings. In flies, the hind wings are reduced, and only the fore wings are functional for lift generation, the hind wings having been modified into stalked structures, called halteres, which vibrate like gyroscopes and assist in stabilizing the insect while in flight [10]. Although flies have only one pair of wings, the wings are extremely powerful and efficient. They will not be able to fly if they lose their wings by the raindrop collision. Fig. 6 shows the dynamics of water droplet colliding with fly's wing surface. In Fig. 6, the drop diameter is D = 2.3 mm and the impact velocity is 2.3 m/s. After the drop has collided with the wing surface of fly, the wing deflects downwards (t =

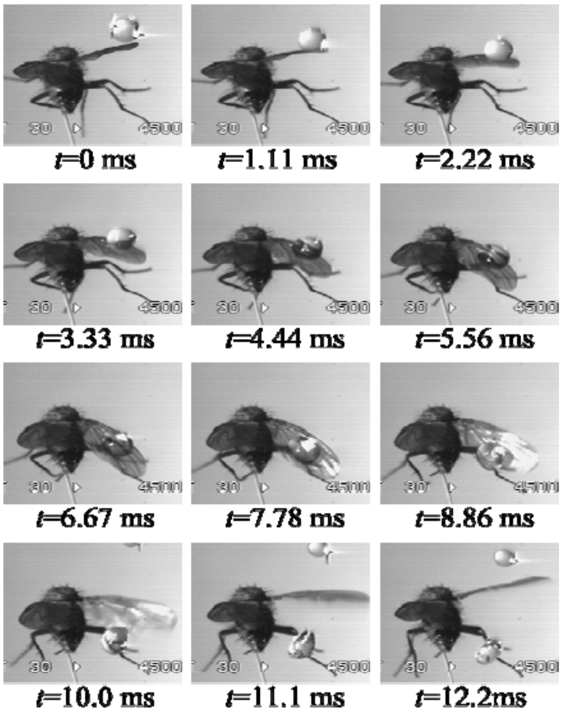

Fig. 6 Sequence of photographs showing the collision behaviour of water drop.

1.11-7.78 ms). The water droplet is deformed throughout its impact. The droplet slips down by the deflection of the wing (t = 8.86-10.0 ms). The deflection of the wing recovers throughout the descent of the droplet from the surface (t = 11.1-12.2 ms). The wing surface does not get wet throughout the drop impact. It can be seen from Fig. 6 that the surface of fly wing has the very high water repellency (the lotus effect).

3.3 Observation of Wing Surface

Winged insects distend their wings by forcing blood through the network of veins. Each wing consists of two thin membranes that are fused together and supported by the stiff network of veins. The fly wings are generally thin and transparent and have the same principal veins as those of other insects. They also have a few crossveins. The wing surface of a fly, *Muscina stabulans*, was observed by using the confocal laser scanning microscope. In the experiment, only the upper surface of the fly wing was observed. When an insect wing is taken in the flow at a certain angle of attack, the under surface roughness hardly affects the aerodynamic lift. The flow collides directly with the under surface of insect wing during the downstroke of wing beating. However, the upper surface roughness of the insect wing has important effects on aerodynamic performance. The air flow over the insect wing generates forces of lift and drag. At a higher angle of attack, the surface roughness is closely related to the turbulent flow generated over the upper surface. Fig. 7 shows the microscopic photographs in six points on the right wing. It can be seen from each photograph that the wing is clothed in minute hairs. In Fig. 7, N is the number density of minute hair. When a liquid droplet contacts such a rough surface, the liquid may not penetrate fully into the surface texture, but rather rolls off the surface, as shown in Fig. 6. Minute hairs on the fly wing enhance the liquid-repellency of the surface, and create the superhydrophobic surface. In general, the superhydrophobic surface consists of microbumps formed by convex papilla epidermal cells [11]. Fig. 8 shows the number density distribution of minute hairs along the costa. In Fig. 8, l_x is the one-dimensional coordinate, with the origin at the wing root. The number density depends on the place of the wing. Many insects have a streamlined profile body in order to reduce the drag. But friction also has its uses. In flying insects, frictional forces within the boundary layer promote smooth or laminar airflow over the surface of the wing. It seems that the inclination of minute hairs shows the direction of airflow in the boundary layer. The vein forming the costal wing margin is costa (leading edge). The costa is the main longitudinal vein, and it is thicker as compared with other veins. Fig. 9 shows the microscopic photographs of leading and trailing edges of the fly wing with 4.5 mm length. At the microscopic level the leading edge is composed of a lot of minute hairs. These hairs that compose the leading edge are comparatively thick and short (0.057 mm in length and 0.014 mm in diameter at the root). Some longitudinal veins form the wavy surface, and its shape should enable it to catch the wind.

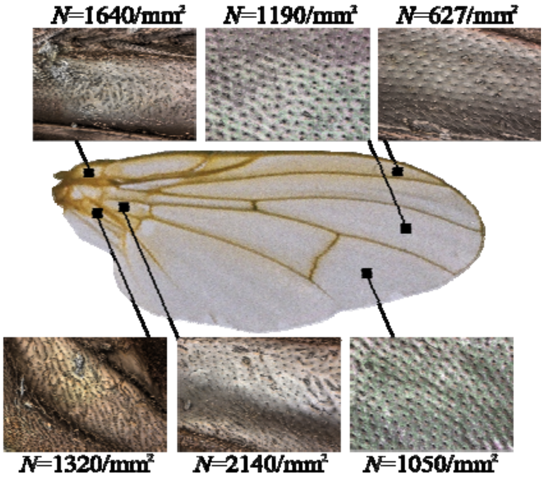

Fig. 7 The details of the surface texture of fly wing.

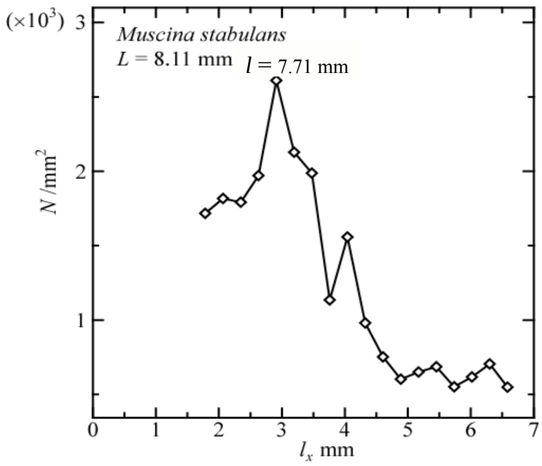

Fig. 8 Number density distribution along the costa.

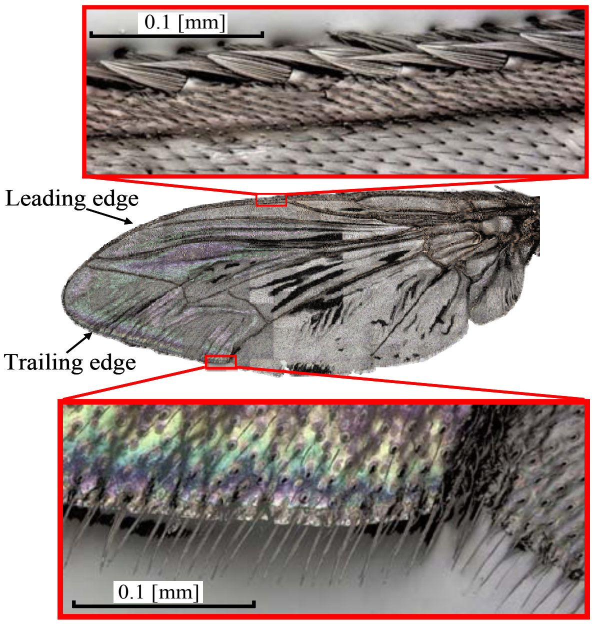

Fig. 9 Microscopic photographs of leading and trailing edges of fly left wing.

The wavy surface brings the wing flexibility. Any modification of the wing surface which increases air resistance within the boundary layer will promote laminar flow and prevent the formation of turbulent eddies. The number of micro hairs is 59 per mm along trailing edge on the surface of wing. The back side surface of the wing is clothed in same number hairs. The wing is designed to withstand the dynamic stress imposed upon its fabric by its own weight and vibration.

4. Conclusions

The wing characteristics of flies were investigated by using the high-speed video camera system and the confocal laser scanning microscope. The results obtained are summarized as follows:

(1) The wing of fly, *Muscina stabulans*, shows the elastic bend deflection throughout its ascent. There is anisotropy in the elasticity of the fly wing;

(2) The wing of fly shows flexibility for the drop collision. The surface of fly wing has the very high water repellency;

(3) The wing of fly is clothed in minute hairs. The number density of minute hair depends on the place of the wing;

(4) The wing of fly forms the wavy surface which consists of veins and thin membranes.

Acknowledgments

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