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THE DRAGONFLY FLIGHT BY A PAIR OF WINGS AND FREQUENCY CHARACTERISTICS OF WINGS

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ABSTRACT

This paper describes the dragonfly flight by a pair of wings and the frequency characteristics of dragonfly wings related to the aerodynamic characteristics. In the first place, free flight by two pairs of wings and a pair of wings of dragonflies was analyzed with a high-speed video camera system. It was confirmed that the dragonfly can fly by a pair of wings. In the second place, the tethered flight of a fly was also studied for comparison. It was confirmed that insect wings undergo strong deformation during the flight. In the third place, the surface shape of dragonfly wings was measured by the three-dimensional, optical shape measuring system. It was clear that the difference of elevation was especially remarkable between the longitudinal veins at the leading edge part. In the fourth place, the dynamic responses of dragonfly wings to the excitation vibration were examined over the relatively wide range of frequency. It was found that natural frequency of dragonfly wings was related to the flapping frequency of the dragonfly.

Introduction

The importance of the study of the locomotion function of animals is well recognized with respect to a variety of scientific fields. In particular, the study of flying function of insects is of fundamental interest and importance with respect to a variety of engineering applications. Extensive investigations on the flight mechanisms of a great many insects have been conducted by a number of researchers [1][2]. Weis-Fogh has observed the hovering motions of the chalcid wasp *Encarsia formosa*, and proposed a new mechanism of lift generation [3]. Lighthill has devised an ingenious explanation for the fluid dynamic processes whereby certain insects are able to generate large lift coefficients by use of the so-called “clap and fling” mechanism [4]. Azuma et al. analyzed the mechanical characteristics of the beating wings of the dragonfly by the simple method based on the momentum theory and the blade element theory [5]. They carried out the theoretical analysis of flight performance at various speeds as well [6]. In our previous papers, the wing structure and the aerodynamic characteristics of an in-flight dragonfly were examined using a scanning electron microscope and a small low-turbulence wind tunnel [7]. Some general principles of functional wing morphology based on quantitative observations were also examined [8]. The measurements of displacement and frequency of extrinsic skeleton vibration produced by wing flapping of a wasp were made by an optical displacement detector system, and the free flight of the wasp was analyzed by a three-dimensional motion analysis system [9]. In spite of many investigations, however, there still remains a wide unexplored domain. Research data on free flight by a pair of wing of dragonfly, detailed measurement of the surface shape of dragonfly wings, frequency characteristics of dragonfly wings, and so forth, are sparse, and there are many points which must be clarified.

In this study, free flight by a pair of wings for a dragonfly was studied by the high-speed video camera system. The surface roughness of dragonfly wings was measured by the three-dimensional, optical shape measuring system. Frequency characteristics of dragonfly wings were studied by a vibration-testing system.

Experimental Apparatus and Procedures

1. Free Flight Analysis

Experiments on free flight analysis were conducted with 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 control unit, a video cassette recorder, a video monitor, and a personal computer. In the experiment on the free flight by one pair of wings, a pair of wings of dragonfly was cut off with scissors. Then the dragonfly was released. The free flight behavior of the dragonfly can be gained by using the high-speed video camera. A series of frames of free flight of the dragonfly were analyzed by a personal computer. In this paper, the tethered flight of a fly was also examined for comparison. Test insects for the flight analysis were the dragonfly, *Sympetrum infuscatum*, and fly, *Lispe orientalis*.

2. Vibration Test of Dragonfly Wings

Frequency characteristics of dragonfly wings were studied in this paper. A block diagram of the experimental apparatus is shown in Fig.2. Experiment was performed on a vibration testing system. The electrodynamic shaker was operated by the automatic vibrating controller at a given frequency, displacement and acceleration within the range of maximum exciting acceleration 784m/s^2, maximum exciting amplitude 25mm, and maximum exciting frequency 3000Hz.

The dragonfly wings were cut from the body. The severed wings were bonded to the wooden base. Bonding was limited to the joint part in the root of the dragonfly wing. Experiment was conducted under the vertical vibration to the wing surface. The displacement of the wing vibration was measured with the optical displacement detector system. The output signal from the photodetector was simultaneously analyzed by a fast Fourier transform analyzer.

3. Surface Shape Measurement

The surface roughness of dragonfly wings was measured by the three-dimensional, optical shape measuring system [10]. This measuring system is composed of an automatic focus microscope with a laser beam driving servomechanism and the high accuracy XY-stage.

The test wing was severed from the insect body before the measurement and mounted on the XY-stage. When the laser beam impinges on the surface of the test wing, a diffused or scattered reflection occurs. The scattered light reflection is then focused through an objective lens on a unique semiconductor sensor. The output signal from the photodetector gives the position of the measured surface relative measurement to the gage probe. A three-dimensional measurement of the wing was made by scanning of the XY-stage.

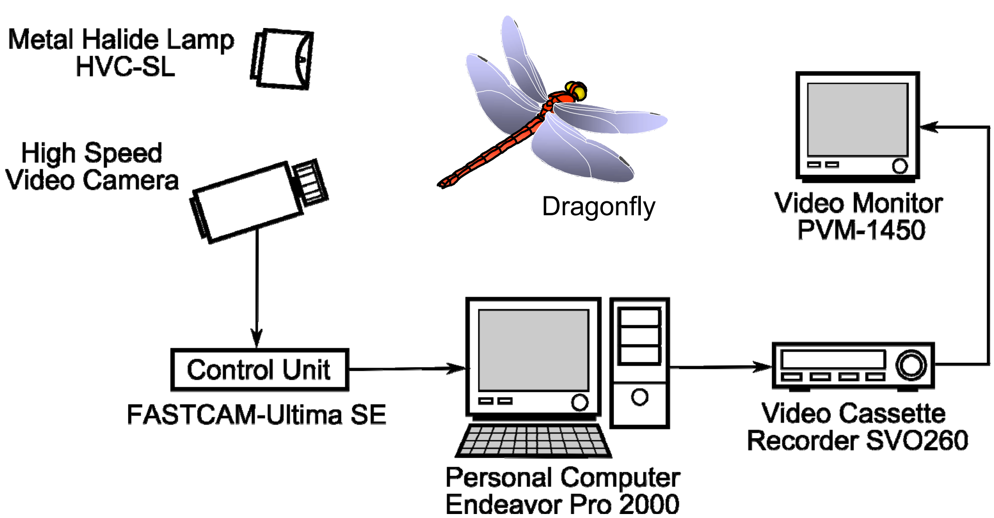


Fig.1 Block diagram of experimental apparatus for free flight analysis.

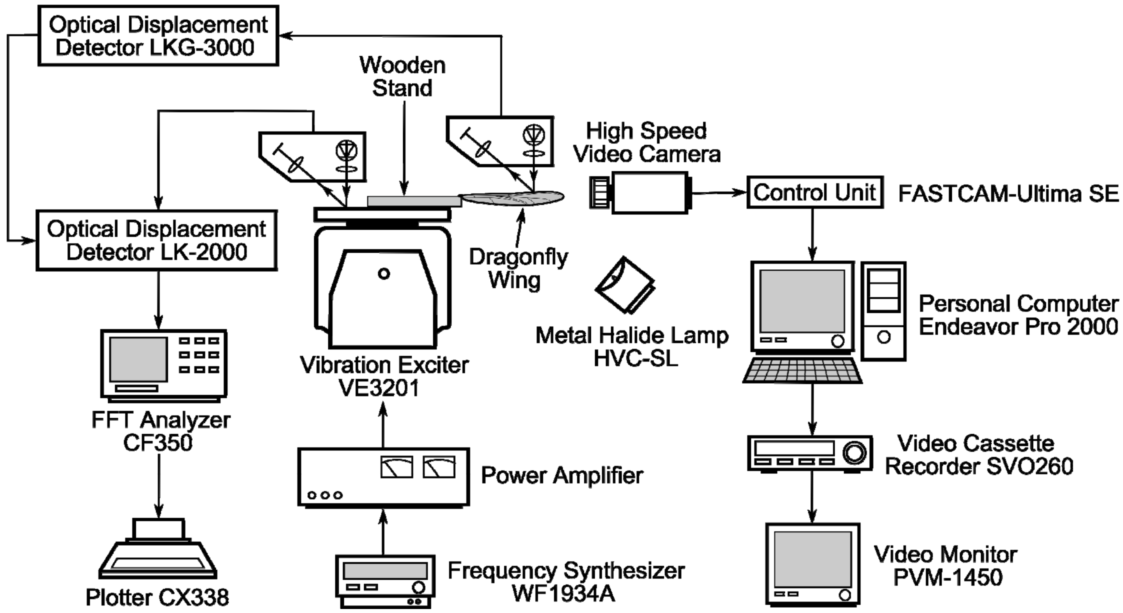
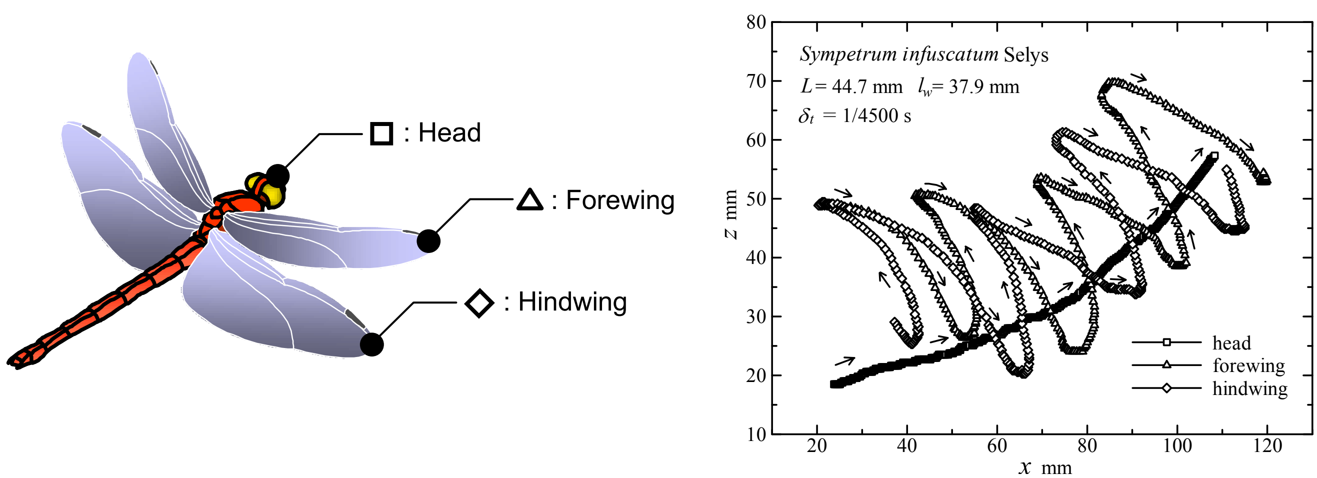


Fig.2 Block diagram of experimental apparatus for frequency characteristics of wings.

Free Fright of Dragonfly

1. The Flight with Two Pairs of Wings

The dragonfly is excellent flyer. The dragonfly represents one of the oldest and most primitive forms of insect flight, with two pairs of wings which can beat independently [11]. In this section, the free flight of a dragonfly was examined using the high-speed video camera system shown in Fig.1. Figure 3 shows the right wingtips and head orbits during the free flight of a dragonfly, *Sympetrum infuscatum*, at the two-dimensional coordinate system x-z. In Fig.3(b), δ_t is the time interval of plotting data in flight movement, L is the body length, and l_w is the wing length of the dragonfly. Orbits in Fig.3 show a rapid climbing flight of the dragonfly. Their wings are deformed in flight and this deformation helps them to maneuver very tight turns and even to suddenly fly. The dragonfly in Fig.3 shows the climbing flight with acceleration. The amplitude of the flapping movement of wingtips changes with the passage of time. In Fig.3, the beating frequency of all wings is 41.3Hz, and the mean flight velocity is 1.14m/s in a direction nearly normal to the stroke plane. Stiffness and deformability of dragonfly wings play an important role in mobile flight.



(a) Measuring points in the dragonfly body

(b) Flight orbit of each point

Fig.3 Trajectories of each point in the dragonfly body during free flight with two pairs of wings.

2. The Flight with a Pair of Wings
Insects are able to undergo a whole variety of flight manoeuvres, and they may use particular styles for different activities [12]. In this section, the free flight of a dragonfly with a pair of wings was examined. The test dragonfly was *Sympetrum infuscatum* as shown in Fig.3. Figure 4 shows a sequence of photographs showing the free flight behavior of the dragonfly with a pair of forewings. In this dragonfly, a pair of hindwings was cut off. It can be seen from Fig.4 that dragonfly wings are deformed through the flapping flight. The abdomen of the dragonfly droops downward during one cycle of the wing flapping. The beating wings of the dragonfly produce a current of air, and the forces acting on the insect as a result of fluid motion through the wings enable the dragonfly to fly.

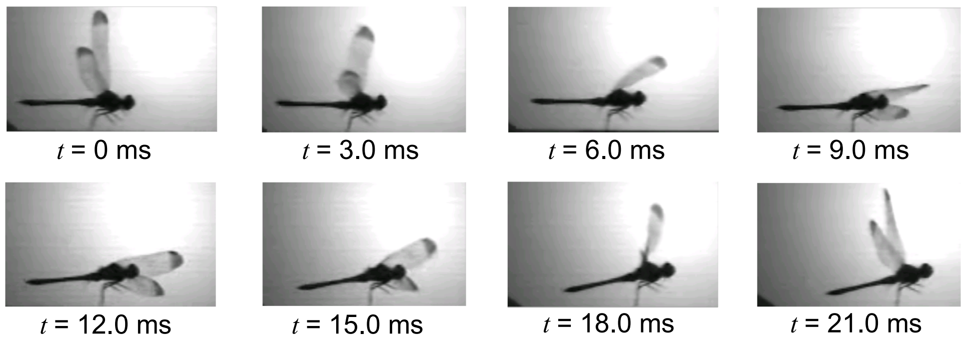


Fig.4 A sequence of photographs showing the free flight with a pair of wings of dragonfly, *Sympetrum infuscatum*.

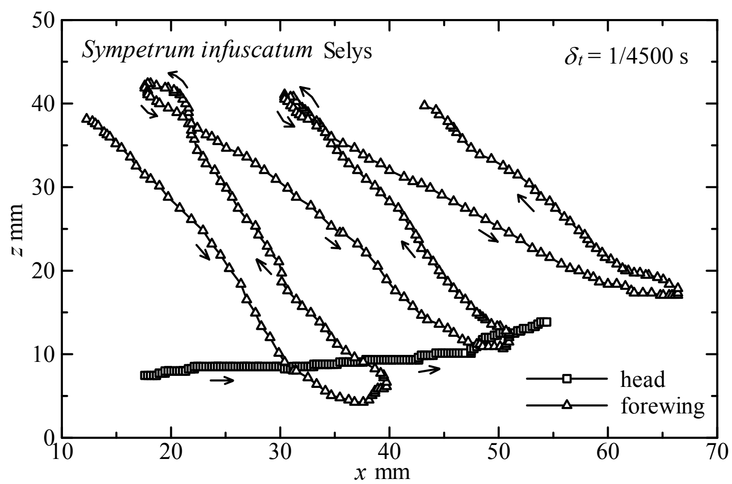


Fig.5 Trajectories of the head and right forewing of dragonfly during free flight with a pair of wings.

Figure 5 shows the right wingtip and head orbits during free flight of the dragonfly at the two-dimensional coordinate system x-z. Orbits in Fig.5 show slow flight of the dragonfly. The dragonfly is doing its best to balance the body in the air. The wingtip trajectory is characteristics in the beginning of each power stroke. The negative lift is not generated, because the dragonfly does not descent. In this experiment, the free flight with a pair of hindwings was also observed. In the flight with a pair of hindwings, the dragonfly curves its abdomen. The abdomen of dragonfly plays an important role in flight balance. In this experiment, it was confirmed that the flight with a pair of wings of dragonfly is possible.

Flapping Behavior of Fly

Flies are insects of the Order Diptera. These insects have just one pair of wings; the hindwings are reduced to small, clubshaped balancing organs called halteres. Flies perform an extraordinary array of complex aerial maneuvers [13]. In this section, flapping behavior of a tethered fly, *Lispe orientalis* Wiedemann, was examined with the high-speed video camera system. The body length of the test fly is L=7.05mm, and its wing length is l_w=5.35mm. In the experiment, the live fly was tethered with a fishing line bonded to the abdomen tip. Figure 6 shows a sequence of photographs showing the flapping behavior of the fly during almost one cycle of the wing flapping. It can be seen that fly wings are deformed greatly in the final stage of the power stroke (t=2-3ms in Fig.6). This deformation is restored to normal conditions as a spring in the next stage of flapping. Figure 7 shows the wingtip orbit during beating of the fly. The Cartesian coordinate system was chosen, with the origin at the fly head, of the upper direction as the z coordinate axis, and the left wing direction as x coordinate. In Fig.7 the time interval of plotting data is constant. It can be seen that the orbits of a power stroke and a recovery stroke during beating are different. Especially, the wing speed

$$v = (dx^2 + dz^2)^{1/2} / dt \tag{1}$$

is larger in the recovery stroke. The flapping behavior of the dragonfly with a pair of wings resembles the flapping of flies.

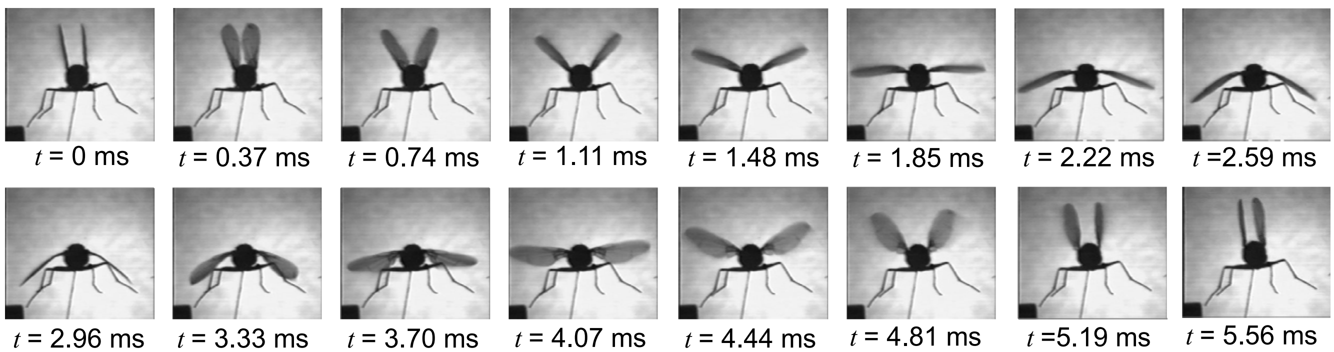


Fig.6 A sequence of photographs showing the flapping behavior of the fly, *Lispe orientalis* Wiedemann.

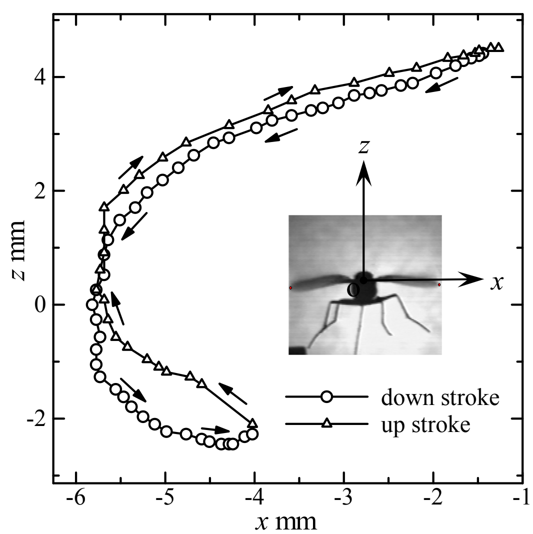


Fig.7 Wingtip path during tethered flying. The arrows show the direction of movement.

Wing Shape of Dragonfly

Rees pointed out that the insect wings are not a plane surface [14]. The morphological functions underlying insect wing design are closely related to some principles of insect flight. In this section, the surface roughness of dragonfly wings was measuring system [10]. Figure 8 shows the three-dimensional display at measurement result for the left forewing surface of the dragonfly, *Sympetrum infuscatum* Selys. In Fig.8, (X_0, Y_0, Z_0) is the orthogonal coordinate system on the XY-stage of measuring system. The color code in Fig.8 shows the height from the surface of XY-stage basis. In general, most insect wings are composed of veins and membranes that are identical on the upper and under surface. 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 airflow over the insect wing generates forces of lift L_f and drag D_f;

$$L_f = \frac{1}{2}\rho V^2 \cdot C_L \cdot S \tag{2}$$

$$D_f = \frac{1}{2}\rho V^2 \cdot C_D \cdot S \tag{3}$$

where ρ is the density of air, V is the velocity of airflow, and S is the wing area. C_L and C_D are lift and drag coefficients. Drag coefficient is described as follows;

$$C_D = C_{D0} + C_{Di} = C_{D0} + \frac{1}{\pi\lambda_e} C_L^2 \tag{4}$$

where C_{D0} is the minimum drag coefficient, C_{Di} is the induced drag coefficient, and λ_e is the effective aspect ratio. Deformation of wing changes the value of these coefficients. Thin and light wings of insect make modification easily. Figure 9 shows the close-up of the wing of a dragonfly, *Pantala flavescens* Fabricius.

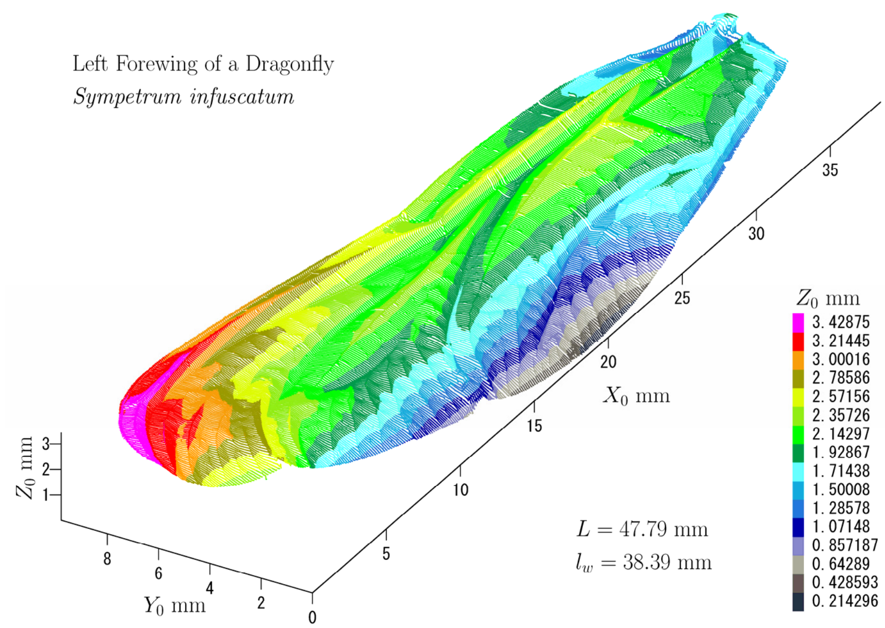
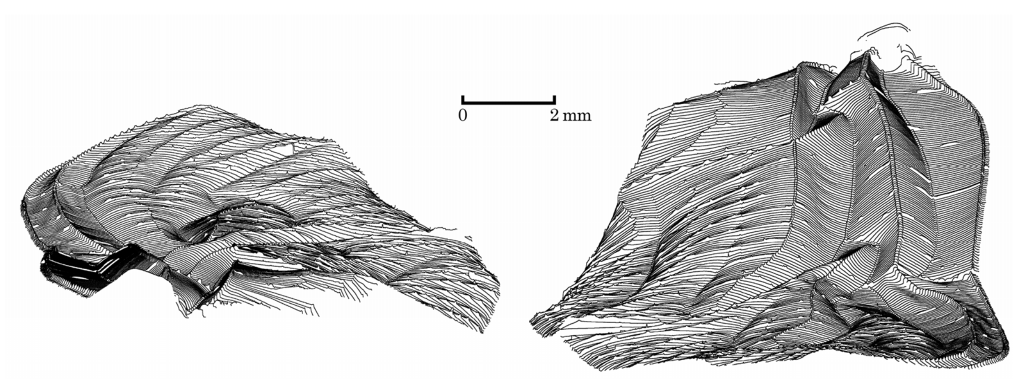


Fig.8 Three-dimensional description of the shape measurement for left forewing of dragonfly.



(a) (b)

Fig.9 Close-up of the right forewing of dragonfly, *Pantala flavescens* Fabricius.

Figure 9 (a) shows the view from the root of the wing and Fig.9 (b) shows the view from the wingtip. The longitudinal vein branch and a rugged topology are observed along the veins. Such wing structure generates bending and torsion of insect wings with flapping and feathering motion. The wings of any flying insect must generate lift and thrust to support the insect's weight and drive the body forward against drag. The wing structure of dragonfly is designed to bear the aerodynamic force and moment without diminishing its performance during beating flight.

Frequency Characteristics of Dragonfly Wings

Frequency characteristics of dragonfly wings were examined in this section. The dragonfly wing was assumed to undergo a vertical vibration to the wing surface with displacement x given by

$$x = x_0 \cos \omega t \tag{5}$$

where x_0 is the amplitude, and ω is the excitation angular frequency ($\omega_0=2\pi f_0$, f_0 is the excitation frequency). In the experiment, the response amplitude of wing vibration was measured at the certain point on the wing surface. Figure 10 shows the relation between the dimensionless amplitude of the dragonfly forewing and the excitation frequency f_0. In Fig.10, $\varepsilon_{\max}$ is the maximum amplitude of wing vibration. It can be seen that the response amplitude depends on the excitation frequency. The spectrum of the response amplitude has peak at f_0=82Hz. This peak frequency is closely related to the function of wing deformation. Figure 11 shows also the relation between the response amplitude and the excitation frequency for hindwing of dragonfly. The peak frequency in Fig.10 and Fig.11 are identical irrespective of size and shape of the dragonfly wings. The peak frequency in the frequency characteristics is twice of the flapping frequency of the dragonfly. This fact reveals that the dragonfly wings are deformed easily at the frequency $2f_i$, where f_i is the flapping frequency of insects. The dragonfly wings receive the aerodynamic force during the flapping motion of wings. In general, the airflow over an insect wing generates of lift and drag. The resultant of these two forces depends on the angle of attack. At the angle 0°, lift and drag are low. As the angle of attack rises, lift initially increases fasten then drag so the lift/drag ratio is a maximum at a certain angle of attack. In down stroke of the wing motion, the lifting force acts on the upper surface of insect wing. In up stroke of the wing motion, the aerodynamic force acts on the under surface of insect wing. The dragonfly wings receive the aerodynamic force twice through the cycle of flapping motion. The wing form changes through flapping motion, and the wing modification changes the lift and drag coefficients of insect wing.

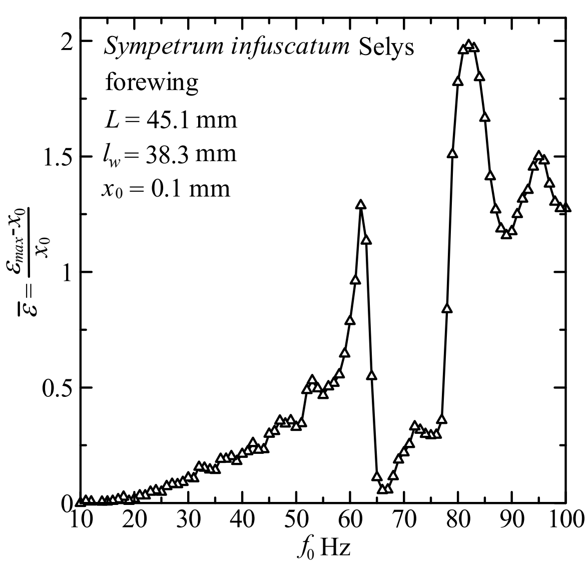


Fig.10 Excitation frequency vs. response amplitude of dragonfly forewing.

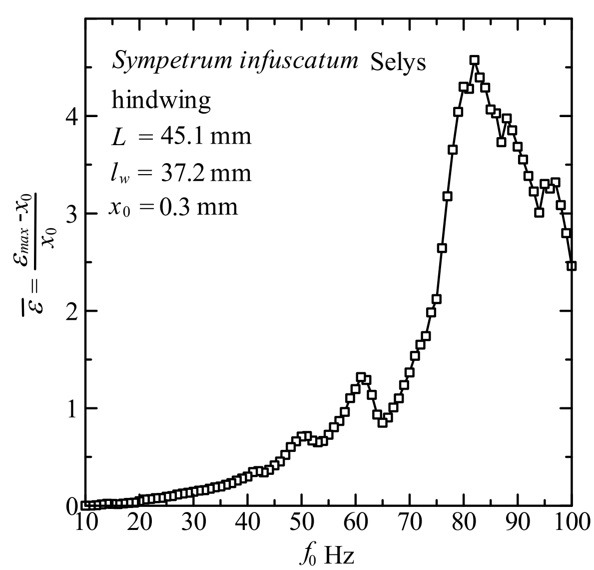


Fig.11 Excitation frequency vs. response amplitude of dragonfly hindwing.

Conclusions

Free flight with a pair of wings the dragonfly, *Sympetrum infuscatum* Selys, was analyzed with the high-speed video camera system. The surface roughness of dragonfly wings was measured by the three-dimensional, optical shape measuring system. The dynamic responses of dragonfly wings to the excitation vibration were examined over the wide range of frequency. The results obtained are summarizes as follows;

(1) The dragonfly can fly in the air by one pair of wings. The dragonfly with one pair of wings balances using his abdomen. The dragonfly lost his hindwings droop his abdomen downward during free flight.
(2) The ups and downs on the wing surface of dragonfly are formed along the veins, and the difference of elevation is especially remarkable between the longitudinal veins.
(3) Frequency characteristics of dragonfly wings show the peak at a certain frequency. The peak frequencies of forewing and hindwing are identical irrespective of size and shape of the dragonfly wings. The peak frequency in the vibration test of the wing corresponds to the twice of flapping frequency of dragonfly.

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