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Flow Mechanism around a Dragonfly

Hiroaki MOCHIZUKI, Makoto MORITA, Kyoichi MASUDA*[1] and Izumi KUSAMICHI**[2]
(*Laboratory of Agricultural Physics*)
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Introduction

When compared to airplanes or helicopters, birds and insects are capable of showing superior performance to their flights since they can change rapidly their flight speed or flight direction including hovering and somersaulting. This is due to the fact that man-made flight objects generate lift and thrust by the fixed wings, whereas flight animate beings generate them by the flexible wings for which they are possible to change easily flapping angle, inclination, and the form of the wing while flying. To clarify flight styles of birds and insects, a lot of investigations have been reported so far[1)~11)]. As an example, Azuma[9,10)] set a dragonfly in a wind tunnel and observed its flapping style and flow state. But the relation between the flapping and the flow states has been left almost uncharted until now. So in the present experiment, the motion of the flapping wings of a dragonfly and the flow state generated by the flapping are observed by a high-speed video camera and a film camera in cases of three kinds of flights, horizontal, upward and downward. From the results of the obsevation, the relation between the motion of flapping of the wing and the flow state was analyzed and discussed.

Experimental Apparatus and Procedure

The wind tunnel used in the present experiment is schematically shown in Fig.1. The air is sucked into the inlet of the wind tunnel from the left side as shown by an arrow and is exhausted into the atmosphere after having passed through the test section and a fan (which generates air-flow). The length of the test section is 2100 mm and the cross-section is square duct with the size of 330mm × 330mm. A smoke wire with 0.28 mm in diameter fixed at the distance of 550 mm downstream of the inlet is streched perpendiculaly from the center of the upper wall to that of the lower wall. Paraffin liquid is intermittently dropped from the top of the wire and 20 volt. is applied to the wire, and then multi-smoke parallel lines generate and flow downstream. These smoke lines reach the leading edge of the forewing of the dragonfly (Pantala flavescens) which is set at the distance of 30 mm downstream of the wire, and then pass through the trailing edge of the hindwing. In passing through the wings, the smoke lines comes to be spread and disturbed due to the flapping of the wings. The flow pictures at an instant visualized like this were taken by a camea (Type F2 NIKON) at exposure time 0.001 sec. Adding to this, the movement and the frequency of the flapping were measured by a high

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*[1] Kagoshima Prefectural Government 14-8, Uchiuma, Kanoya, Kagoshima
**[2] Japan Interface 11-21, Nishisengoku, Kagoshima

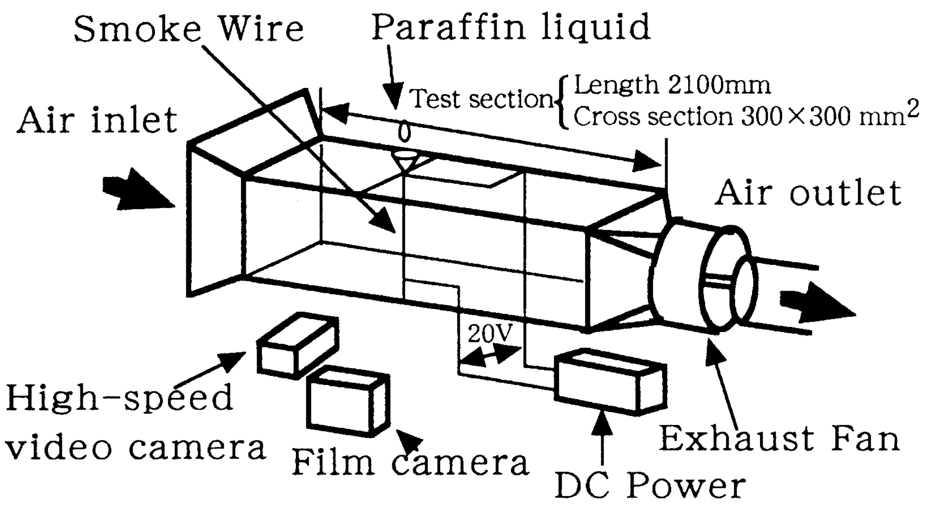


Fig.1. Experimental apparatus.

-speed video camera (Type FASTCAM-hvc PHOTRON).

The contours of the dragonfly are shown in Fig.2(a) and (b) as the plane and side views, respectively. Although the wings have rough surface with small convexities and concavities, the thickness is only 0.14 mm at the leading edge of the forewing supplied with maximum thickness. Therefore, the wings can be regarded as, so called to be film wings. In the present experiment, the smoke passes through the pterostigma of the forewing at 20mm downstream of the smoke wire, with no flapping of the wings kept horizontally.

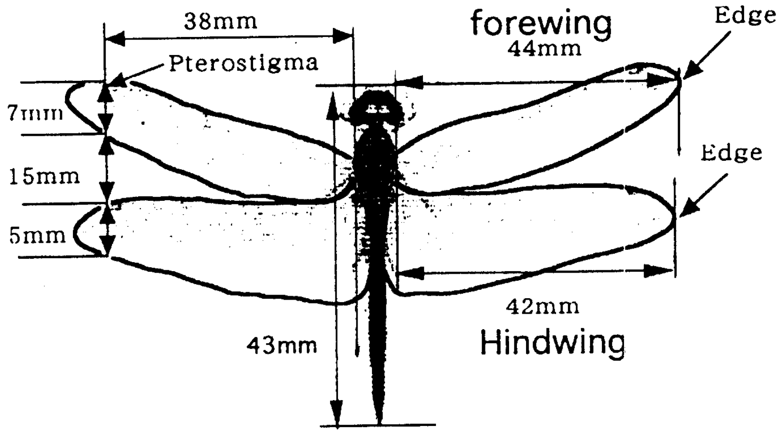
Experimental Results and Discussion

Flapping of wing

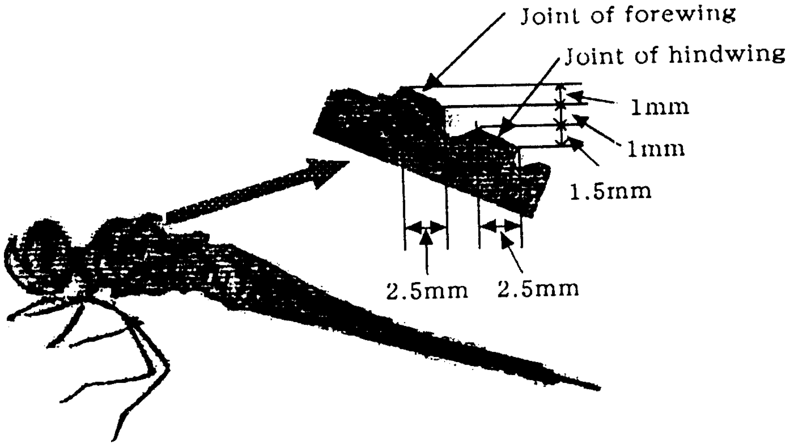
An example of the movement of the wings taken by the high-speed video camera (720 frame/sec) is shown in Fig.3. This figure is observed from the left side as indicated in Fig.2(b), and the figures (a) and (b) represent one cycle of oscillation of the forewing and the figures (c) and (d) the hindwing. Both the abscissa and the ordinate are the distance from the head of the dragonfly. The joint of the forewing is located at the spot about 5 mm higher than abscissa and the hindwing at that about 3 mm higher. The frequency of the flapping for the fore- and hindwings are about 33 Hz, and the forewing flaps at about 90°. later than the hindwing.

Now, in Fig.(a) which represents the downstroke of the forewing, the tip of the wing right over the joint moves to left-upside as shown by the states of ① to ② and begins to move left-downside from the state ③, and then it flaps with almost the same inclination toward the state ⑧. The orbit of the tip in such downstroke as this is drawn by a dotted line.

Next, in Fig.(b) which represents the upstroke of the forewing, the tip moves almost perpendicularly upward from the state of ⑨ to that of ⑩, and then after it has changed the movement left-upside from the state of ⑩ to that of ⑪, it moves from the state of ⑫ to that of ⑮ with almost the same gradient. The orbit of this upstroke is drawn by a dotted line.



(a) Plane view



(b) Side view

Fig.2. Contour of dragonfly. (*Pantala flavescens*)

From the movements of the wing, the mean flapping angles are about 100° above the horizontal and 40° below, i.e. through total angles of 140°. Also, the flapping mean velocity of the tip is about 3.2 m/s in the downstroke and about 3.8 m/s in the upstroke. From this result, it is confirmed that the difference of the velocity between the downstroke and the upstroke affects the lift and the thrust.

In Fig.(c), the hindwing at the normal state as indicated by ① moves left-downward to the state of ⑥ with a sharp gradient, and then moves almost normally from the state of ⑥ to that of ⑧. The mean velocity of the tip is 3.2 m/s in this downstroke.

Next, in Fig.(d), the tip moves almost normally upward from the state of ⑨ to that of ⑪ with almost the same trace as in the case of the downstroke, and then moves right-upward to the state of ⑱. From the movements of the wing, the mean flapping angles are 80°. above the horizontal and 58° below, i.e. through total angles of 138°. The mean velocity of the tip is 2.8 m/s in this upstroke. A trace of the tip of the hindwing moving like this is shown by a dotted line in the figure, The movements of the fore- and hindwing tips shown by the dotted lines are drawn in the same figures (a) and (b) in Fig.4, respectively. As evident from Fig.4,

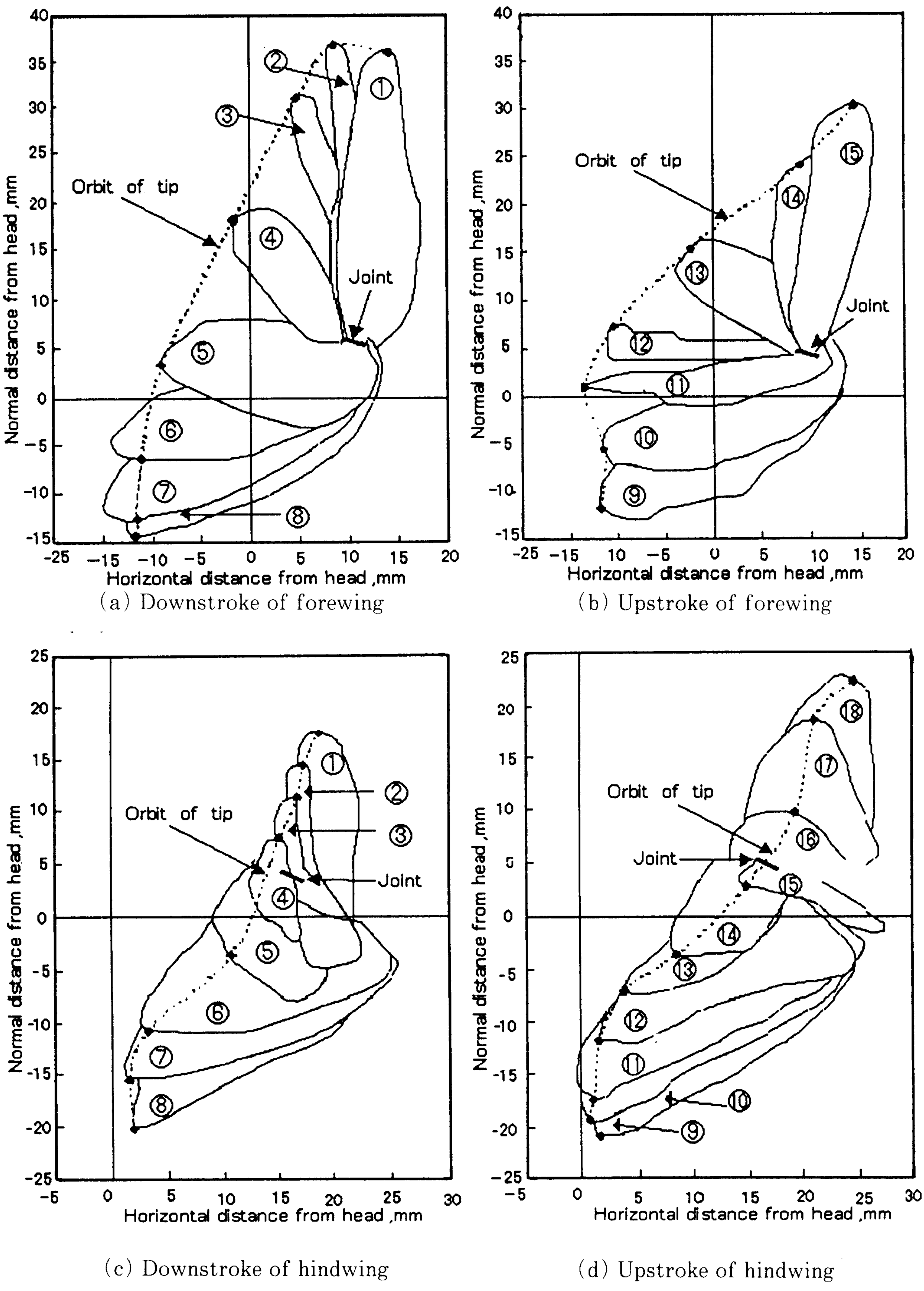
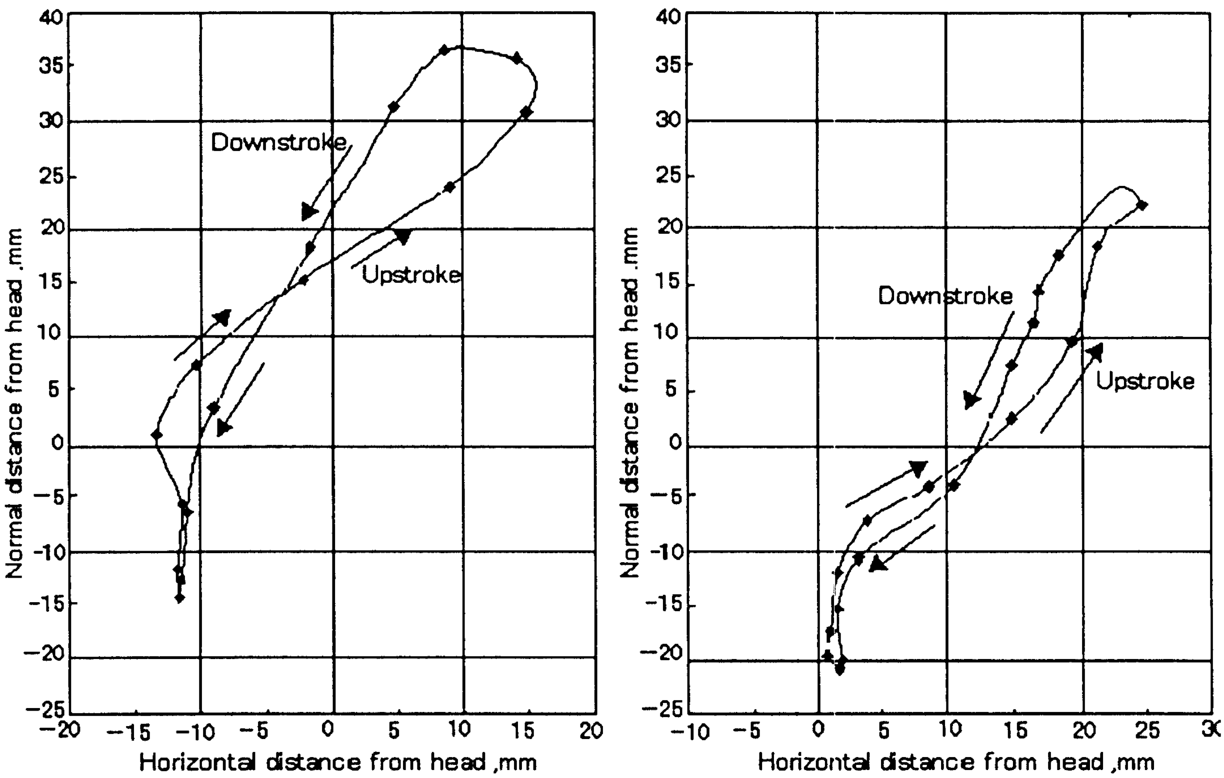


Fig.3. One cycle of flapping of dragonfly.



(a) Forewing (b) Hindwing

Fig.4. Orbits of one cycle of wing tip.

it can be confirmed that the fore- and hindwings flap the up- and downstrokes drawing a letter of "8". Moreover, the gradient of the downstroke is greater than that of the upstroke. This means, as described before, that the lift is produced by the difference of the gradient between the down- and the upstrokes.

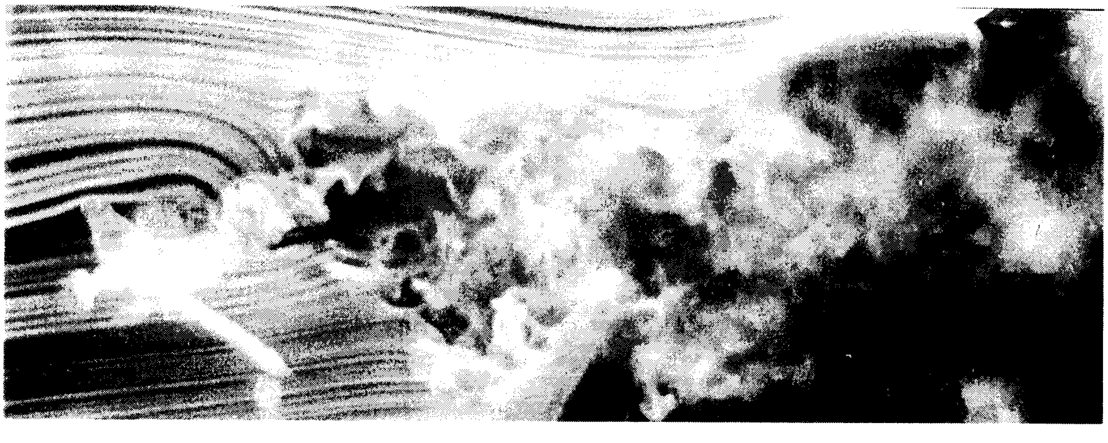
By the way, the detailed movements of the flapping during smoking in the horizontal-, upward- and downward flights could not be clearly observe due to the veiling by the smoke flow. However, it may be concluded that the gradient of the downstroke for the horizontal flight is greater than that in the upward flight and smaller than that in the downward flight.

Flow Generated by Flapping of Wing

The flow pictures which were taken by the film camera for three cases corresponding to the horizontal-, upward- and downward free flights in the air are visualized and shown in Figs. 5 (a), (b) and (c), respectively. In Fig. (a), the parallel flow lines over and under the body represent uniform flow not affected by the flapping. However, the flows entering around the body are drawing curves toward the head or the wing. This means that the air around the body is exhausted by the flapping letting the air newly flow into the region, causing the inflow to draw the curve. Moreover, the curvature of the inflow at the upside of the body is larger than that at the downside of it. This is due to the fact that the gradient of the downstroke is larger than that of the upstroke so that a greater amount of air is exhausted downward by the downstroke above the horizontal in comparison to the one below it, fetching

(a) Horizontal forward flight

(b) Oblique upward flight



(c) Oblique downward flight

Fig.5. Flow patterns generated by flapping of wing.

in largely curved inflow at the upside of the body.

Next, in Fig. (b) showing the flow state for the oblique upward flight, the flow at the upside of the body enters nearly normally to the body, drawing larger curvature than that for the horizontal flight in Fig. (a). The reason is that when the dragonfly flies upward, it needs to exhaust more amount of air downward than that for the horizontal flight and to suck the same amount of air as the exhausted one, causing the upside to take more accelerated state.

In Fig. (c), the flapping corresponds to that of the downward flight. In this case a little amount of lift force is necessary, so it may need a little amount of inflow causing smaller curvature in comparison with the horizontal- and upward flights. Now, the reason why a larger curvature of the inflow around the body is more clearly observed for the forewing than the hindwing is due to the fact that the flapping angles of the forewing are about 100° above the horizontal and about 40° below. As the result, more amount of air is sucked around the forewing by the downstroke above the horizontal. However, although the flapping angles of the hindwing are about 80° above the horizontal and about 58° below, the inflow around the hindwing has already been disturbed by the forewing. Therefore it can be considered that the downstroke of the hindwing has almost no effect on the direction of the inflow upstream of the head. On the other hand, in the upstroke, both the fore- and hindwings flap with smaller gradient in comparison with the downstroke, so that only a small amount of air may be exhausted by the upstroke. Therefore it may be considered that the curvature of the inflow below the body becomes smaller. Also, the edges of the wake in Figs. (a), (b) and (c) are flowed more downstream at faster velocity than that of the uniform flow. This means that the thrust and the lift were generated by flapping. As described until now, when the dragonfly is flapping with large angle of about 140° for the forewing and about 138° for the hindwing, which corresponds to those in proceeding at full speed in free flight, it can be considered that the wake largely disturbs in the horizontally backward-, downward- and upward directions depending on each flight style, respectively.

Now, the flapping observed and discussed in the present experiment corresponding to the flight at full speed is only one movement in various kinds of flapping, for example, a horizontal, upward and downward flights with no flapping, a high-speed flight with a little flapping, a hovering without flapping against wind, a somersault, a backward flight occuring when a dragonfly begins to fly from a leaf and a sideward flight, etc. Although these flights are very important to clarify the flight and flow mechanisms of the dragonfly, they have not yet been studied so far. So, more detailed observations are necessary to discuss accurately about the flight of the dragonfly.

Summary

The flapping of the wing of the dragonfly and the flow generated by the flapping at full speed were observed by the high-speed video camera and the film camera. As the result, the relation between the movement of the wing and the flow was analyzed and clarified.

The wings of the dragonfly move one cycle drawing a letter of "8" from the beginning of the downstroke to the end of the upstroke. Moreover, the gradient of the downstroke becomes larger than that of the upstroke, fetching larger velocity of the wing tip for the downstroke in comparison with the upstroke. The wakes generated by such flappings let their flow states the horizontal-, downward- and upward downstream directions depending on the horizontal-,

upward- and downward flights. Almost all the amount of the air which enters into the region around the body and the wing is sucked from the upper side of the wing to compensate the air which has been exhausted by flapping. The edge of the wake generated by the flapping proceeds more downstream at faster velocity than that of the uniform flow. In this way, it can be confirmed that the thrust and the lift are generated by the flappings of the wings.

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