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# The Visualization of the Flow Field through Ship's Propulsion Mechanism of Weis-Fogh Type using the PIV

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**Abstract** : The Flow fields of a ship's propulsion mechanism of Weis-Fogh type were investigated by the PIV. Velocity vectors and velocity profiles around the operating and stationary wings were observed at opening angles of $\alpha$=15° and 30°, velocity ratios of V/U=0.5~1.5 and Reynolds number of $Re=0.52\times10^4 \sim 1.0\times10^4$. As the results the fluid between wing and wall was inhaled in the opening stage and was jet in the closing stage. The wing in the translating stage accelerated the fluid in the channel. And the flow fields of this propulsion mechanism were unsteady and complex, but those were clarified by flow visualization using the PIV.

**Key words** : Fluid machinery, Propulsion mechanism, Flow visualization, PIV, Unsteady flow

## 1. Introduction

The Weis-Fogh mechanism, discovered through the analysis of wing motion in the hovering flight of a small bee called Encarsia Formosa, is a novel and very efficient mechanism for lift generation[1],[2].

Figure 1 shows the principles of the motions. Here, the bee is able to remain hovering flight by moving its wings in a horizontal plane while holding the body upright. First, the wings clap from the dorsal side of the body revolving around their leading edge. Then, they open their wings from the state where the trailing edges are touching each other(fling), move in the horizontal plane while maintaining a fixed open angle(we define the fixed open angle as 1/2 of the angle formed by intersection of two wings in the second one of Fig. 1). The wings change their moving direction and the opening angle on the ventral side(flap) and then move back to the horizontal plane and clap touching their leading edges again. These motions are repeated. The lower picture of Fig. 1 shows a 2-dimensional model of this movement. Generally, wings in a still state need some distance in order to gain

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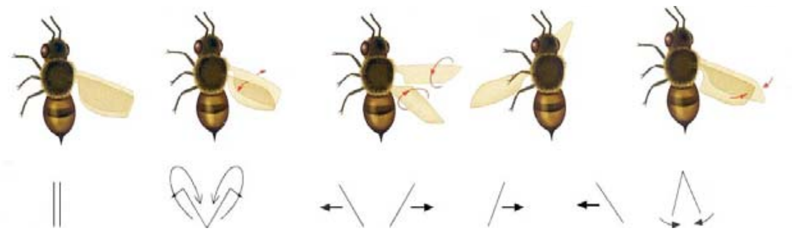


Fig. 1 Hovering flight of Encarsia formosa

sufficient circulation around the wing for generating lift (Wargner effect). This is the case in airplane wings. However, in this mechanism, a pair of opposite circulations around wings is generated at the moment when the two wings opening touching their trailing edge. This enables the wings to gain sufficient lift in spite of short stroke. Tsutahara[3],[4] presented the propulsion model, which used a two-dimensional model of the Weis-Fogh mechanism in the water channel, and showed that this propulsive device operates very effectively by conducting experiments on the dynamic characteristics, and a working test on a model ship as the new ship propulsion system. Ro[5],[6] simulated the unsteady flow fields by applying the vortex method on the circumference of the wing while the propulsive mechanism was being operated, and also verified the pressure around the wing and the time variation of the thrust and the drag on the wing.

But in calculation the limitation ;opening angle α=30°, velocity ratio V/U=1.0 kept from the investigation of various flow field, And for the practical use of this propulsion mechanism, it is necessary to clarify the flow field. Hence this experiment would contribute to the practical use of the propulsion mechanism as clear visualization of flow field with parameters.

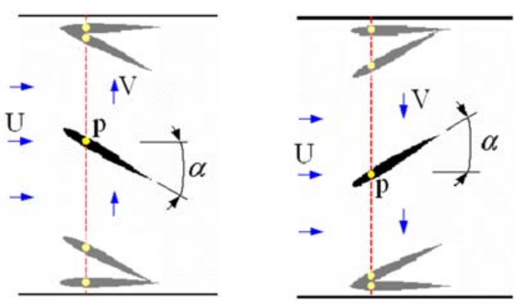
## 2. Experiment device and method

### 2.1 Model of the propulsion mechanism

Figure 2 shows the model of a Weis-Fogh type ship propulsion mechanism.

Perpendicularly, the figure shows the upper part of the model, and, as a wing in the water channel oscillates in a reciprocal operation, the propulsive power rises to the left (the direction towards which the ship is progressing). This model is identical to the Tsutahara et al. model[3], and so a brief synopsis of it will be sufficient.

A wing is installed in a square channel. When the point $p$ corresponding to the center axis of the wing is oscillated back




(a) Up stroke (b) Down stroke

Fig. 2 A model of propulsion mechanism

and forth along the y-axis, the wing first opens at point $p$ from the lower surface (opening stage). Then, maintaining an open angle α, the wing moves translationally in a parallel movement (translating stage), and finally rotates and closes on the upper surface (closing stage) through the reciprocal motion of point $p$. It then executes an opening stage at the upper surface once more, moves translationally once again, and repeats the closing stage at the lower surface.

Originally, in the Weis-Fogh mechanism as shown in Fig. 1, circulation in the opposite direction is formed at each position of wing, as a pair of flat-plate wings open while their trailing edges touch. However, through the principle of a mirror image, when channel walls are placed and the same motions as above are executed by a single wing, as shown in the propulsion model of Fig. 2, the identical effects can be achieved with a pair of wings.

### 2.2 Driving system of the wing

Figure 3 shows the schematic diagram of the driving system of the wing.

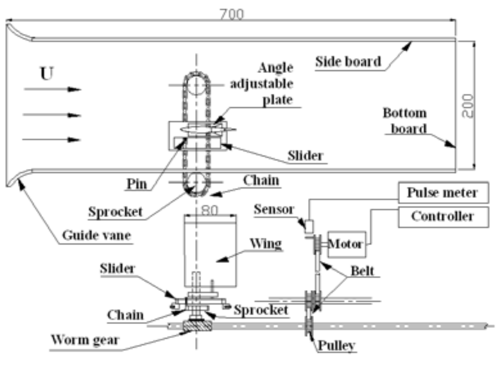



**Fig. 3 Driving system of wing (unit: mm)**

The device was assembled to have the same wing motion as the previously explained propulsion mechanism model, and it was made as following for easy visualization experiment.

The wings were taken the shape of NACA0010 with transparent acrylic panel, which has a chord length of 80mm, span of 100mm and thickness of 10mm. The wing has a hole located at a point 0.75 away from trailing edge to link the axis.

Water channel is 200mm in width, 700mm in length, and 250mm in height the entrance of water channel has a guide vane for smooth flow.

The side board of water channel was made of transparent acrylic panel for good permeation of light. The bottom board, which didn't have to be permeated with light was painted black. Some parts of the driving system were installed under the bottom board.

Meanwhile, in the method of driving of a wing, as shown in picture, power of motor spins the chain through belt, pulley, worm gear and sprocket.

The reciprocating motion of the slider where the axis of wing is attached was done with a pin that is fixed on the upper part of the chain.

Also, the wing is being linked to the axis of wing, therefore when the slider does the reciprocating motion, the moment would generate around the axis of wing to open the wing. For keeping a fixed opening angle, adjustable plate was attached to the upper side of the slider.

The movement velocity of the wing was controlled by voltage of direct current, and the motor's rpm was calculated by proximity sensor and pulse meter.

### 2.3 Visualization experiment by PIV

Figure 4 shows the schematic structure of experimental device by the PIV.

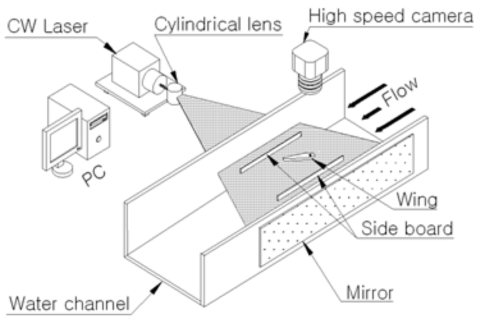



**Fig. 4 Schematic structure of experimental device**

In this experiment, driving system of a wing shown as Fig. 3 was installed in water channel of circulating water tank flowing uniform flow, enabled clear visualization.

In detail, after installing the driving system of a wing in the water channel, sheet light made of CW laser was thrown on vertical and horizontal direction with uniform flow outside circulating water tank, and field was taken a picture by high-speed camera in a vertical direction with the upper side of wing.

A spherical shape PVC with 100 ㎛ average diameter and 1.02 specific gravity was used as chasing particle. High speed camera's model is PHOTRON's FASTCAM 1280 PCI, laser is JENOPTIK's Jenlas D2.8, and table 1 shows the main specification of PIV system. The experiment conditions were fixed that the opening angle of a wing $\alpha=15°$ and $30°$ with the Reynolds number $Re=0.52\times10^4 \sim 1.0\times10^4$, and the ratio of wing speed(V) to uniform flow(U) of V/U=0.5~1.5.

**Table 1 Main specification of PIV system**

| Item | Specification |
|---|---|
| Image board | Fast Cam-X panel link board drive |
| Light source | 8W continuos wave laser |
| Sheet light | Cylindrical lens: Ø3.8×11.4mm |
| Resolution | 1280×1024pixel |
| Software | CACTUS 3.2 |
| Error vector(%) | Average: about 0.1% |

## 3. Results and discussions

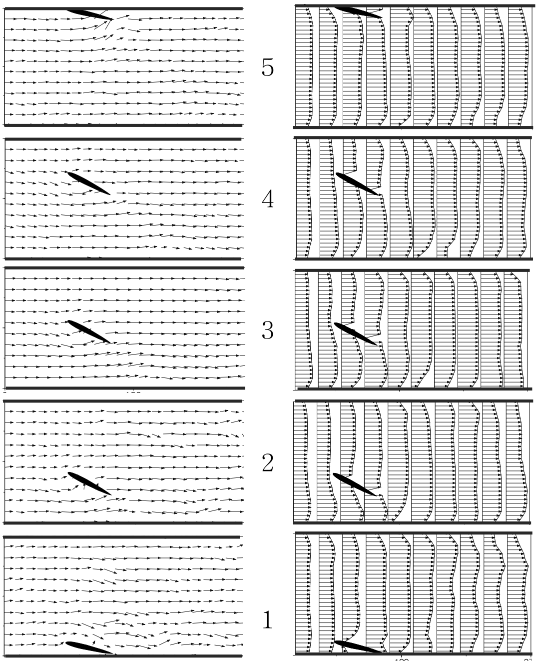
Figure 5 shows the continuous flow pattern around the wing (NACA0010) during one stroke for Re=7,000, the Reynolds number Re as defined by the wing chord and uniform flow.

In Fig. 5, (a) refers to the velocity vectors and (b) represents the velocity profiles under the same conditions as in Fig. 5 (a). In Fig. 5, 1 represents the opening stage; 2 to 4, the translating stage; and 5, the closing stage.

First, as seeing the velocity vector, the velocity vector around the wing turn towards the direction of movement of the wing in all process, showing that experiment matches the results of simulation.

Seeing the velocity profile, flow pattern of the upper stream side and downstream side of wing has similar shape in all process, but velocity profile length of the downstream side of wing is longer than that of the upper stream side of wing.

These show that as the wing moves, it accelerates the fluid movement in the water channel, which indicates that the propulsion mechanism functions effectively as a pump.




(a) Velocity vector (b) Velocity profile

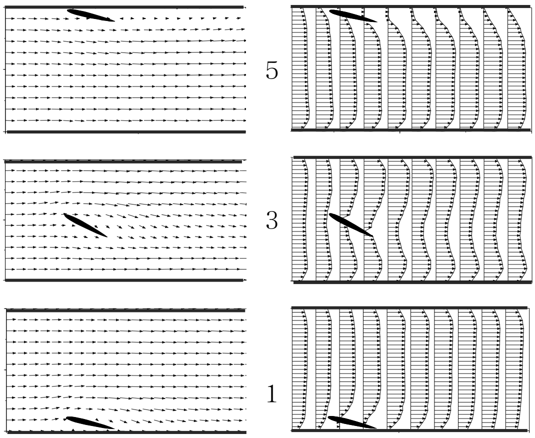
**Fig. 5 Flow pattern for one stroke of the wing (H=2.5C, rp=0.75C, V/U=1.0, α=30°)**

Also, during the process of opening between the wing and the wall, fluid was inhaled, and when closing, fluid was jet. This will be considered specifically in Fig. 7 and Fig. 10 where it was photographed in a close-up.

Figure 6 shows the flow pattern around the stopped wing in same condition of Fig. 5.

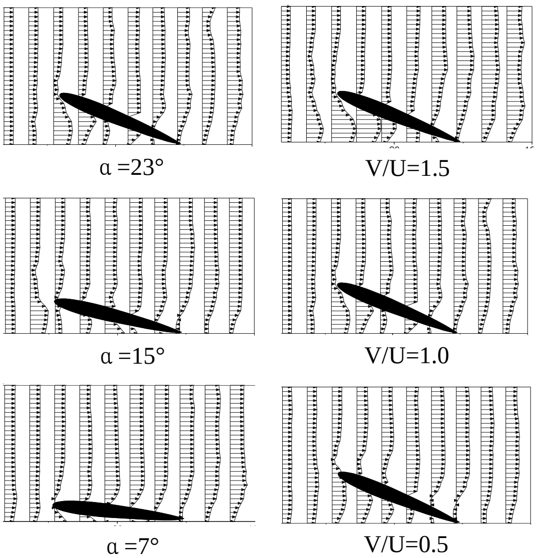
In comparing with the pictures 1,3,5 in Fig. 5 and the pictures 1,3,5 in Fig. 6, when the wing moves, it accelerates fluid in the channel while the wing stops, it simply moves as a resistance. It is clearly showing especially in the Fig. 6(b) velocity profile of the wing's wake.

Figure 7 shows a velocity profile of changing the opening angle α and a ratio of velocity V/U photographed up close in




(a) Velocity vector (b) Velocity profile

**Fig. 6 Flow pattern around the stationary wing ($Re=0.7\times10^4$, α=30°)**



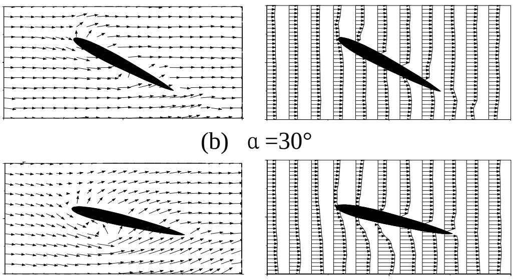

(a) V/U=1.0 (b) α =23°

**Fig. 7 Velocity profile around wing with α and V/U at the opening stage**

a process of opening. Fig. 7(a) is the velocity profile with fixed ratio of velocity V/U=1.0 and the opening angle of α=7°, 15°, 23°.

As indicated from the figure, fluid between wing and wall is inhaled in a process of opening, and flow velocity of fluid accelerates as the opening angle increases. Fig. 7(b) is the velocity profile of the opening angle of α=23° with the ratio of velocity of V/U=0.5, 1.0, 1.5. As indicated from the figure, the larger the ratio of velocity, the larger flow velocity between wing and wall at the opening stage.

Figure 8 shows flow pattern of the opening angle of α=15° and α=30° photographed in a close-up when the wing came at the center of water channel during a translating stage.


(b) α =30°

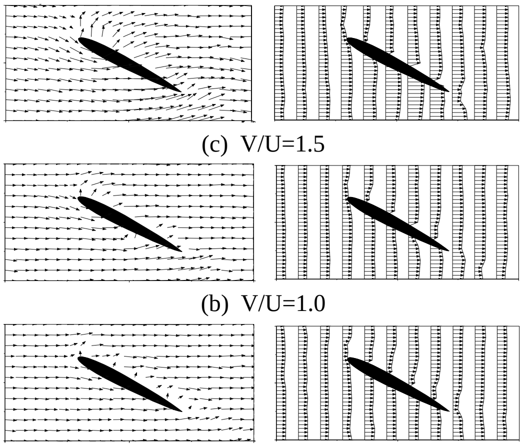
(a) α =15°

**Fig. 8 Velocity vector and velocity profile around wing with α at the translating stage (V/U=1.0)**

Comparing the velocity vector, in case of the opening angle of α=15° velocity vector around the wing turns towards more to the direction of wing movement than in case of the opening angle of α=30° The scale is also larger. Seeing velocity profile, in case of the opening angle of α =15° velocity profile accelerated more of fluid of the pressured side to the uniform flow than in case of the opening angle of α =30°.

Examining the boundary layer around the pressured side of wing to uniform flow in velocity profile, in case of α=15°, differently in case of α=30°, it shows that the flow separated in the vicinity of the leading edge reattached in the vicinity of middle of the wing.

Figure 9 shows flow pattern with the ratio of velocity V/U in case of the opening angle of α=30° in same condition as Fig. 8.


(c) V/U=1.5

(b) V/U=1.0

(a) V/U=0.5

**Fig. 9 Velocity vector and velocity profile around wing with V/U at the translating stage (α=30°)**

Seeing velocity vector, it indicates the fluid around the wing has the same direction with the movement of the wing, and the larger the ratio of velocity, the faster the movement velocity of fluid is.

Seeing velocity profile, when the wing moves in a translating stage, it shows accelerating fluid of the pressured side to uniform flow, the larger the ratio of velocity, the more accelerating fluid is.

Figure 10 shows the velocity profile with closing angle a and ratio of velocity V/U photographed up close in the closing stage. Fig. 10(a) is velocity profile of the closing angle of α=23°, 15°, 7° with the fixed ratio of velocity of V/U=1.0. As

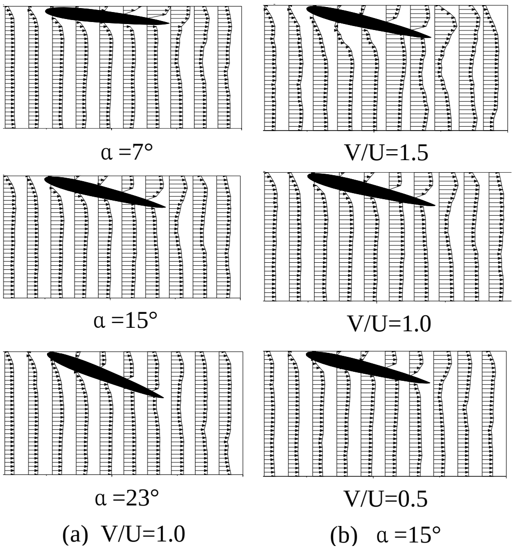



**Fig. 10 Velocity profile around wing with α and V/U at the closing stage**

indicated from the figure, fluid which locates between wing and wall is spouted in closing stage, and effusion velocity of fluid increases when the closing angle decreases. Fig. 10(b) is velocity profile at the closing angle of α=15° with the ratio of velocity of V/U=0.5, 1.0, 1.5. As indicated from the figure, the larger the ratio of velocity, the larger jet between the wing and the wall is in the closing stage. This happens because the larger the ratio of velocity, the faster the closing of a wing. Especially in the case of V/U=1.5, the flow is separated in the vicinity of leading edge of the pressured side because of high wing speed.

## 4. Conclusion

The Flow fields of a ship's propulsion mechanism of Weis-Fogh type were investigated by the PIV. Velocity vectors and velocity profiles around the operating and stationary wings were observed at opening angles of α=15° and 30°, velocity ratios of V/U=0.5~1.5 and Reynolds number of $Re=0.52\times10^4 \sim 1.0\times10^4$. The Flow fields were considered about each experiment parameter with opening, translating and closing stages. And the results are summarized as following:

(1) When the wing operates, it accelerates the fluid in water channel. But when the wing stops, it acts as a resistance.

(2) Fluid between wing and wall is inhaled in the opening stage, and the suction velocity of fluid increases as the opening angle and the velocity ratio increase.

(3) Fluid around the wing moves in the same direction as the movement of wing in the translating stage, the movement velocity of fluid increases as the opening angle is small and the velocity ratio is large.

(4) Fluid of pressured side to uniform flow is accelerating in the translating stage, the scale increases as the opening angle is small and the velocity ratio is large.

(5) Fluid between wing and wall is jet in the closing stage, and the jet velocity of fluid increases as the closing angle is small and the velocity ratio is large.

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## References

[1] Weis-Fogh, T., "Quick Estimates of Flight Fitness in Hovering Animals, Including Novel Mechanism for Lift Production," Journal of Experimental Biology, Vol. 59, pp. 169~230, 1973.

[2] Lighthill, M. J., "On the Weis-Fogh Mechanism of Lift Generation," Journal of Fluid Mechanics, Vol. 60, Part 1, pp. 1-17, 1973.

[3] Tsutahara, M. and Kimura, T., "An Application of the Weis-Fogh Mechanism to Ship Propulsion," Transactions of the ASME, Journal of Fluids Engineering, Vol. 109, pp. 107-113, 1987.

[4] Tsutahara, M., Kimura, T. and Ro, K. D., "Ship Propulsion Using the Weis-Fogh Mechanism," Bulletin of the Marine Engr. Soc. in Japan, Vol. 17, No. 2, pp. 49-55, 1989.

[5] Ro, K. D., "Calculation of Thrust and Drag Characteristics for Ship's Propulsion Mechanism of Weis-Fogh Type," KSME International Journal. Vol. 14, No. 11, pp.1249-1258, 2000.

[6] K. D. Ro, B. S. Zhu and H. K. Kang, "Numerical Analysis of Unsteady Viscous Flow Through a Weis-Fogh Type Ship Propulsion Mechanism Using the Advanced Vortex Method," Transactions of the ASME, Journal of Fluids Engineering, Vol. 128, pp. 481-487, 2006.

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