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2D-PIV Analysis of Loach Motion and Flow Field

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Abstract : The propulsion methods of the aquatic lives are the results of optimization by evolution and are useful for the design of swimming-robot, etc. Among them, loach has unique propulsion technique both bending its long body and shaking caudal fin. Our purpose of the research is to clarify its swimming mechanism through flow field analysis. Two dimensional motion and flow around it have been experimentally visualized by particle image velocimetry (PIV). Vortices around a loach and the interactions between the loach body and surrounding water are analyzed. Generating and growing vortices by bending its body, it pushes water backward to gain repulsing force, and it seems that moves through vortices reducing the resistance force at the same time. When a vortex reaches to the caudal fin, it accelerates both sides of the vortex pushing water backward and seems gaining propulsion utilizing the caudal fin. After moving forward, loach leaves a vortex street like reverse Karman vortices, which means that loach gains propulsion.

Keywords : Visualization, PIV, Loach.

1. Introduction

Living creatures in water have obtained variety of moving mechanisms adjusting to the change of the environments by evolution through a long time. They gather attention as a research of aqua-bio-mechanism as shown by Bainbridge (1958), Lighthill (1970), Wu (1971), Azuma (1992) for example. Flows around them and the principles of propulsion were analyzed and this information is useful to design robots or actuators.

In general fish swims pushing water backward and forming vortices as shown by Heltel (1963), Kim et al. (1998), Lauder et al. (2002), Bartol et al. (2002) for example. Carangiform fishes such as horse mackerel swim using higher performance large fin. They gain propulsion pushing water backward casting vortices leaving jet-like flow pattern induced by those vortices. On the other hand Anguilliform fishes or other living creatures with long bodies have unique propulsion technique. For example, eel and loach can swim quickly although they do not have large caudal fins. We concentrate on a loach which is unique because, it uses both of its body and caudal fin, it swims at the bottom of still water and it has viscous skin to reduce flow resistance (called Tom's effect). We believe such information will be useful to design robots to inspect pipe lines. Loach generates vortices when it bends its body and may utilize the vortices efficiently for propulsion or energy saving, but the detailed mechanism has not been studied yet.

We made a prompt report about the flow field around a loach (Nagayama et al., 2005). In this paper, flows around a moving loach will be shown using PIV technique. And detailed analysis about the interactions between its body and water will be discussed. The mechanism of propulsion and how vortices relate to propulsion will be studied.

2. Experimental Conditions

Flow around a loach is visualized by particle image velocimetry (PIV), and the experimental set up is shown in Fig. 1. An acrylics tank of 175 x 175 mm size is filled with water up to 10 mm height. As a loach swims in shallow water, the flow field is two dimensional. To visualize the flow, tracer particles basically Orgasol were used. 2 halogen light sheets with 10 mm thickness illuminated from the both sides so that shadows will not appear. Although their light sheets are thick, it is not a problem because we are considering averaged 2D flow in shallow water here. A plastic sheet covered the water surface to prevent the random light scattering on the wave. The loach motion and water flow is monitored by high speed camera from the top with the frame rate of 500 pps, it means the picture interval is 2 ms.

There are many kinds of fish with long body. Among them, Black Kuhli loach, which is shown in Fig. 2, was chosen here. Black Kuhli loach or Pangio Oblonga in scientific name lives in India or South Asia. Its total length is about 60 mm, height is 8 mm and width is 6 mm.

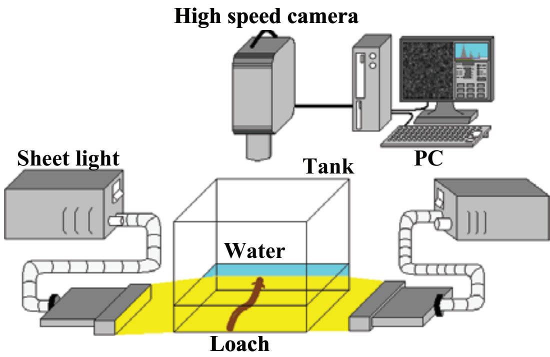


Fig. 1. Experimental Set-up.

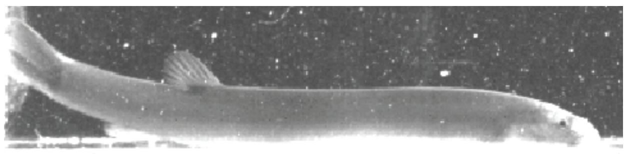


Fig. 2. Black Kuhli Loach (Scientific name: Pangio Oblonga) Distribution : India, South Asia.

Table 1. Experimental Conditions.

	Case 1	Case 2	Case 3
Area	150 x 150 mm	100 x 100 mm	50 x 50 mm
Tracer diameter	Orgasol 50 μm	PVC 100 μm	Orgasol 50 μm

Three cases of visualization were tried as shown in Table 1. Whole or wide area is visualized in Case 1, while detailed or small area is visualized in Case 3. In Case 1, entire flow field around a loach is observed, although detailed velocity in the body can not be detected accurately. In Case 3, enlarged area around the body and the caudal fin can be viewed although it can not cover entire region like Case 1. In Case 3, measuring the velocity distributions on the body, detailed interactions between the body and fluid can be analyzed. The picture size is 1024 x 1024 pixels for all three cases.

3. Results and Discussions

3.1 Analysis of Body Motion

Here the basic characteristics of loach motion are analyzed before discussing about PIV and flow field. Loach conditions are shown in Table 2 using typical or averaged value. The swimming style of the loach of this study object is considered to be classified into the propulsion by changing wave. Reynolds number is about 12900 and Strouhal number is about 0.3. Wave speed is proportional to swimming speed and larger than that as shown in Fig. 3.

Table 2. Loach charactristics.

L: Length [mm]	60
Hight (and Width)[mm]	8 (6)
U: Swimming speed [mm/s]	215
W: Wave speed [mm/s]	259
f: Tail Freqency (Hz)	6.4
l: Tail amplitude (mm)	11.3
Re (=UL/v)	12900
St (=fl/V)	0.3

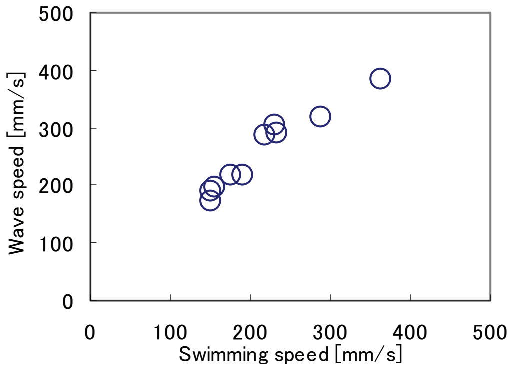
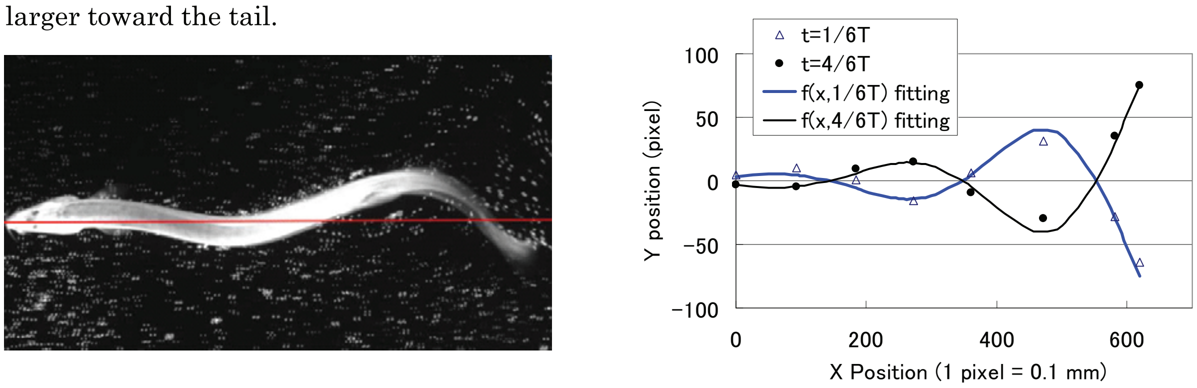


Fig. 3. Relation between wave speed. and swimming speed

$$F(x,t) = 0.4\exp(0.05x)\sin 2\pi(1.46\frac{x}{L} - \frac{t}{T} + 0.32) \tag{1}$$

The characteristic movement during one cycle of the swim of the loach is shown in Fig. 4. Figure 4 (a) is original images of the loach and Fig. 4(b) is results of function fitting using F(x, t) expressed as Eq. 1. Here L mm is body length and T s is time cycle. Constant 1.46 is the wave number. Amplitude of the loach head vertical against swimming direction is small. The amplitude of the wave becomes larger toward the tail.



(a) Original image of a swimming loach. (b) Shape analysis of a loach by function fitting.

Fig. 4.

3.2 PIV Analysis Conditions

Original images are shown in Fig. 5 for three cases. Inside red line area is analyzed by PIV. Analysis conditions are, direct correlation method, correlation region (35 x 35 pixels), search region (9 x 9 pixels), and vector mesh size (12 x 12 pixels). The loach body image is extracted, and vector plots were written on the loach image.

Case 1 (150 mm area) Case 2 (100 mm area) Case 3 (50 mm area)

Fig. 5. Original images obtained by experiments (inside red line is used for PIV analysis).

To discuss the interactions of loach body and water, and velocity vectors should be correctly measured. There are two points which should be appropriately treated. One is the fineness of the picture and the other is the light and dark balance of the picture. Vector plots are shown in Fig. 6. If the mesh is too rough relative to the body, velocity on the body can not be measured like Case 1 with vector mesh size of 1.76 mm. In Case 2, vector number is increased but it is still not enough to express the body velocity. In Case 3, with mesh size of 0.59 mm, vector number is further increased. We can see the continuous vectors in the body and that seems reasonable. The magnitude of vector in Fig. 6 is 0.08-0.1 m/s, which is close to the swimming speed of 0.1 m/s obtained from the head motion.

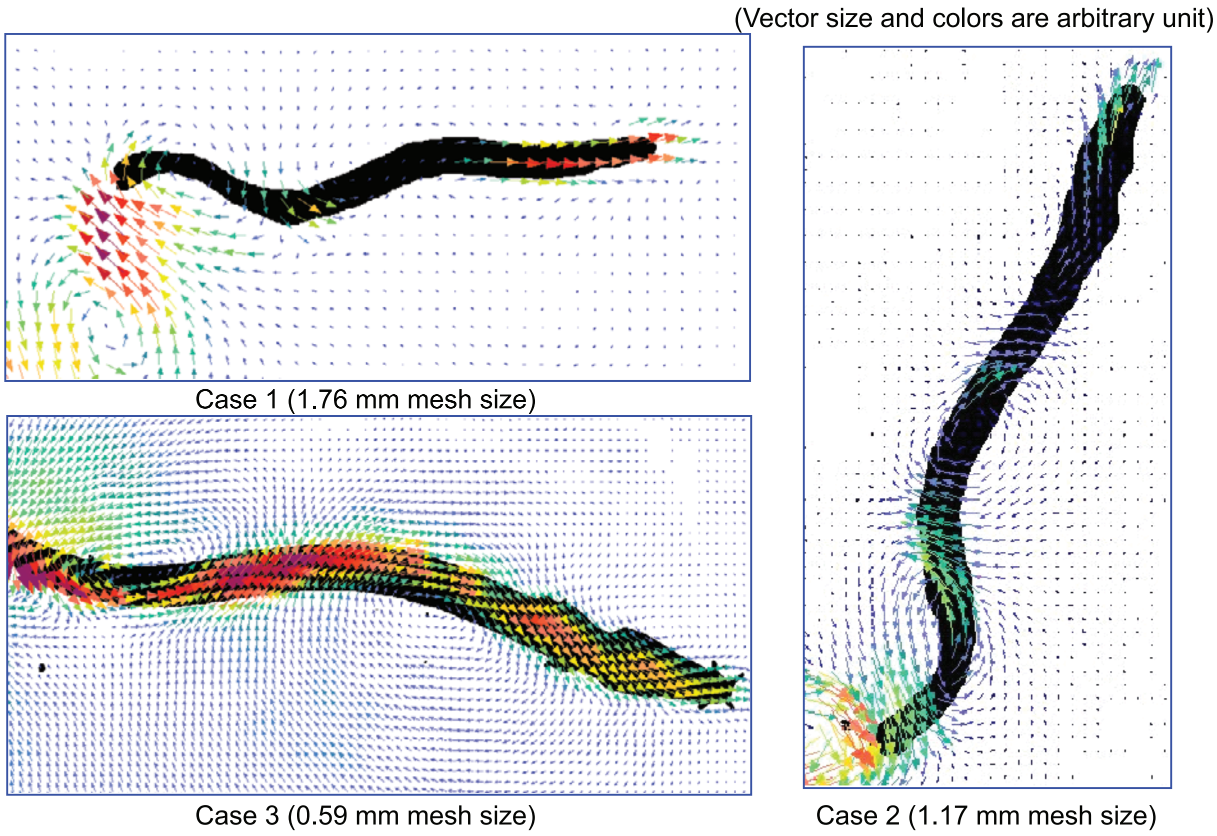


Fig. 6. Vector plots obtained by PIV analysis in Fig. 5.

Another point is the brightness of the loach body and tracer particles which are illuminated by the light sheet. If the loach body is too light or too dark compared to the particles, velocity of the body can not be measured. Adjusting the light, we can see patterns on the loach skin as shown in **Fig. 7**. And pursuing the skin image using PIV processing, velocities of the body can be detected.

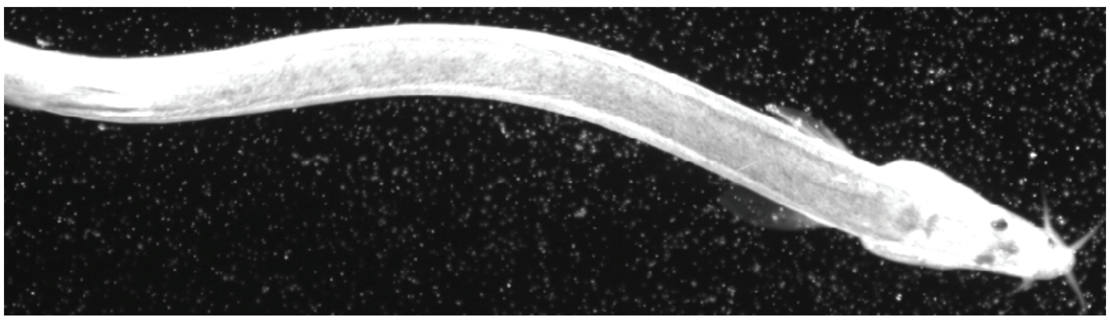


Fig. 7. Enlarged original image of Case 3 in Fig. 5.

Vector mesh size used is 12 pixels as shown in Fig. 6. Vorticity plots obtained from vector plots are also sensitive to mesh size. Too small mesh size causes noisy vector plots and vorticity plot. On the other hand too large mesh size causes the loss of accuracy in results. **Figure 8** shows the dependency of the vorticity plots on the mesh size. Here the flow field is a pair vortex which loach left behind in Case 3. In the case of mesh size 7 pixels, vorticity plots are rather noisy. That might be caused by particle distributions and motions in shallow water. Increasing mesh size to 9 or 13, vorticity plots become smooth, and we can easily observe a pair vortex. Increasing mesh size more to 17, vorticity plots are smooth but clear image is losing. After all vorticity plots obtained from vector mesh size of 9 to 13 seem appropriate and, we use 12 pixels as already shown.

Thus the velocity vector distributions and vorticity plots seem reasonable that means velocity of the loach body can be detected and measured. Then we will discuss about the interactions between loach body and surrounding water.

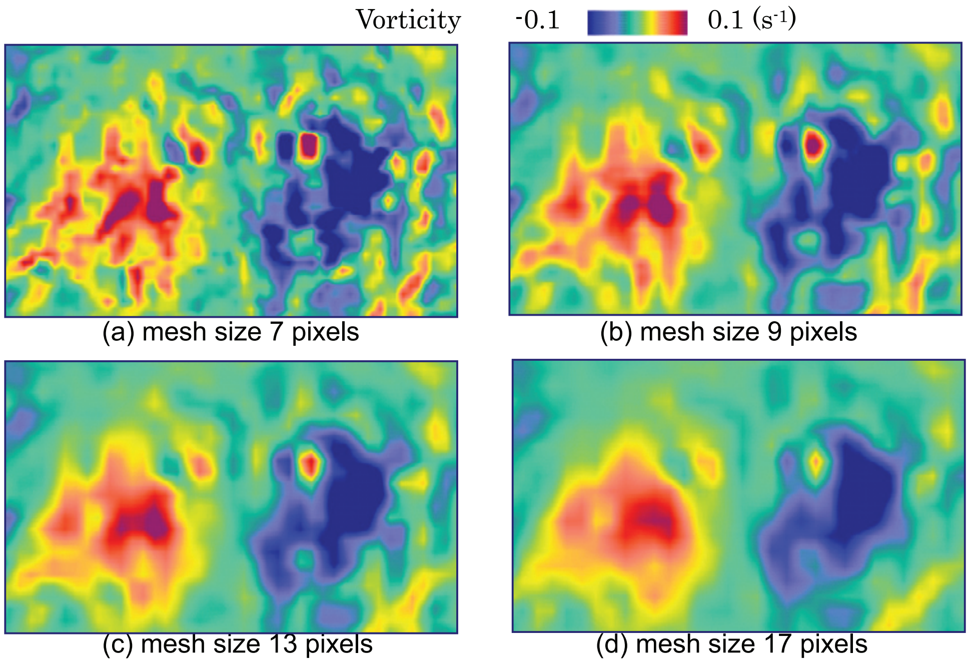


Fig. 8. A pair vortex in vorticity plots dependency on vector mesh size.

3.3 Entire Flow Field around a Loach

Here in Case 2, whole area around the loach including the region after loach left is analyzed. Velocity vector plots and vorticity plots are shown in Fig. 9 during one cycle of 140 ms. The vibration of the loach is small at the head and gradually increases to the fin in amplitude.

Note that propulsive performance is related not only to the vortexes but also to the momentum and pressure change which are not measured. Here we can discuss flows behind the loach as a result of propulsion, and we will also discuss the body and water interaction at section 3.4 and 3.5 using PIV results. As the loach moves, vortices are generated and they are left after the loach moves away. These vortices move slowly backward while the loach moves forward. The vortex street left behind the loach looks like reverse Karman vortex string with jet like flow along swimming center line as shown in vorticity plots in Fig. 9 at t/T = 1. That indicates propulsion force acts on the body as a result of its motion. Compared to fish which swims at high speed casting off vortices and leaving jet like flow pattern induced by those vortices, loach swims slowly, put vortices behind and jet like flow is not so strong.

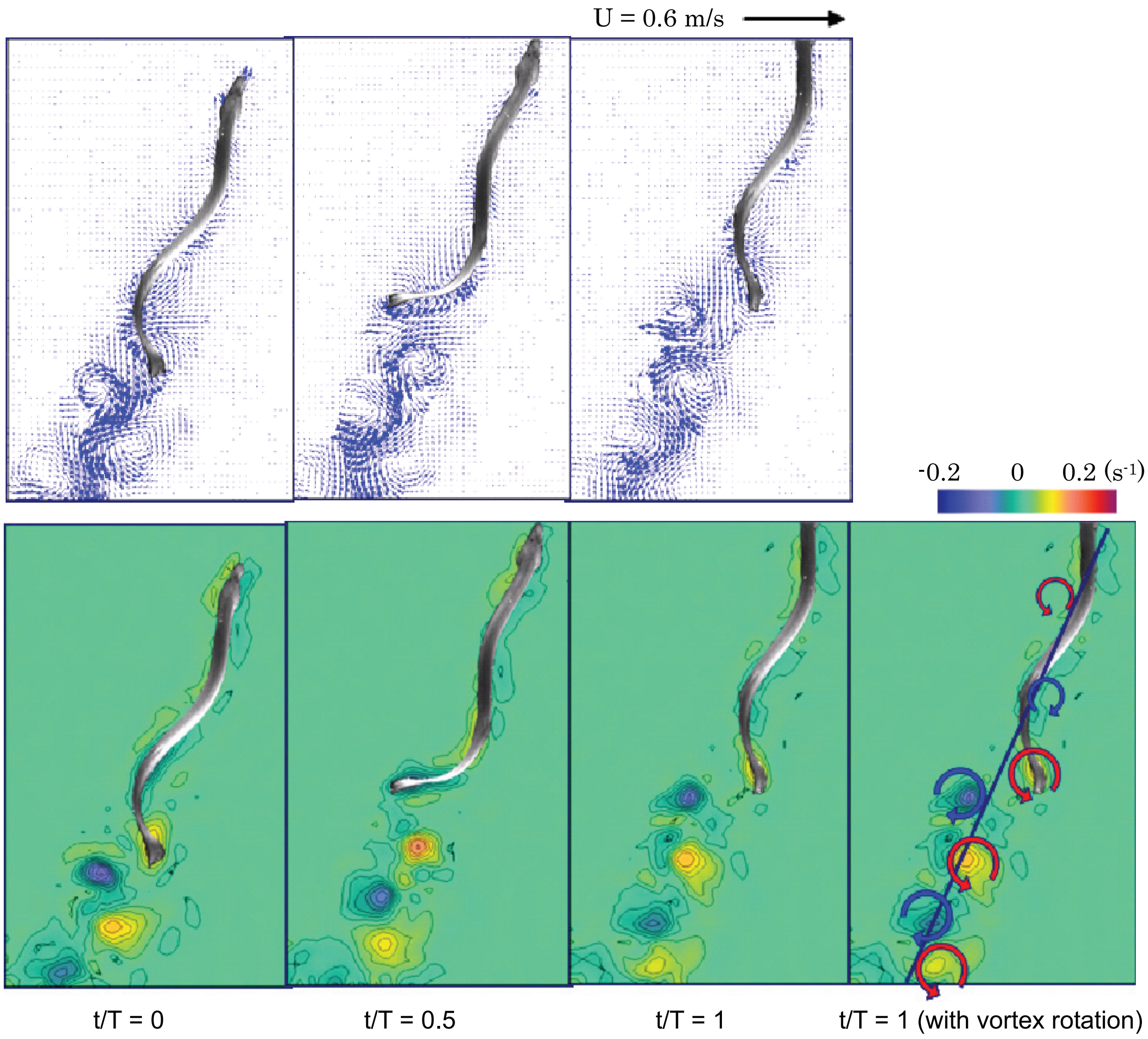
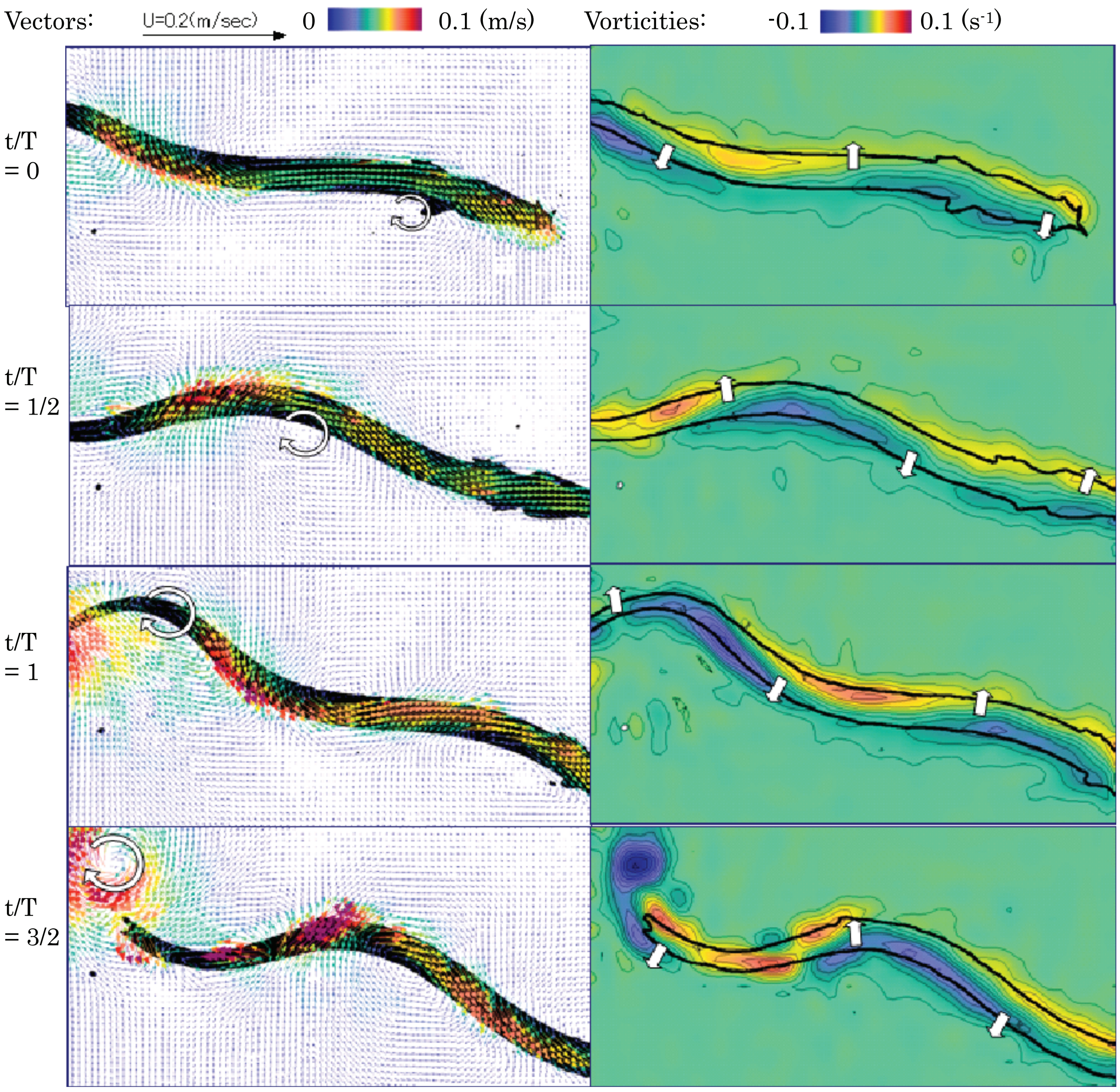


Fig. 9. Velocity vectors and vorticity plots around a moving loach during one cycle.

3.4 Interaction between Loach Body and Fluid

Here in Case 3 of 50 mm area visualization, enlarged area around the body and the caudal fin can be viewed. Measuring the velocities on the body, detailed interactions between the body and fluid can be analyzed as already discussed. Velocity vector plots and vorticity plots are shown in Fig. 10. Single vortex movement is added in vector map, and arrows in vorticity plots shows motion normal to the body. Note that vortex center in vector plot means the center of fluid rotation, while maximum point in vorticity plot means the velocity change is strong. Voriticity has peak around the body and fluid boundary and shear flow is dominant. We like vector plots to analyze vortex motion. Vortex generated at the top position moves downward along its body and finally reaches to the caudal fin. For example, a vortex is shed from head side at t/T = 0, moves along the body side at t/T = 1/2, reaches close to the caudal fin, at t/T = 1, and is leaving from the caudal fin at t/T = 3/2. Most interesting point in Fig. 10 is that the center or core of the vortex generated by vibrations is not along the backbone of the body but the body side. Transmission of the bend backward and the body motion forward by propulsion, are both in the direction to grow and to strengthen the vortex. Thus by pushing the vortex backward, the loach gains propulsion. At the same time, the loach swims through the vortices, and it is clear the vortices helps loach to swim (the effect is called roller bearing effect), although it is difficult to say how much vortices reduces the resistance force. After all, the loach swims not only by using the caudal fins but also by using the whole body.



(a) Vector map with movement of single vortex (b) Vorticities (arrows is motion normal to body)

Fig. 10. Loach motion and flow field (T = 240 ms).

3.5 Detailed Flows around Caudal Fin

Loach and other fishes basically gain propulsion by pushing the water backward and as a result vortices are formed. In the case of loach, vortices transmitted from the upper body to the caudal fin. Here in Case 3, how the loach controls and treats vortex by its caudal fin is studied. Figure 11 shows interactions between the caudal fin and surrounding fluid during a half cycle (T/2 = 120 ms). Figures at the top are vector plots while those at the bottom are vorticity plots. The loach shakes its fin anti- clockwise at t/T = 0. The caudal fin is to release a clockwise vortex in the left side. We can also see another anti- clockwise vortex approaching to the caudal fin after it was carried along the body. There the caudal fin rotates both of these two vortices (one is released to the left, and the other is coming from the body), the reacting force relates the propulsion force. The coming vortex before the caudal fin is also pushed by the body and the reacting force may also work as propulsion. The vortex also seems to help the fin motion by rotating in the same direction. In Fig. 11(b) at t/T = 1/6, the caudal fin finished to release clockwise vortex and anti-clockwise vortex reaches to the caudal fin, in other words the fin is at the center of the vortex. In Fig. 11(c) at t/T = 1/3, the fin moves clockwise and accelerates the vortex rotation. And when the caudal fin leaves vortex, loach extracts the fin smoothly without disturbing the vortex. In Fig. 11(d) at t/T = 1/2, vortex is released from the caudal fin accelerating anti-clockwise vortex rotation. The vortex also helps the fin motion by rotating in the same direction.

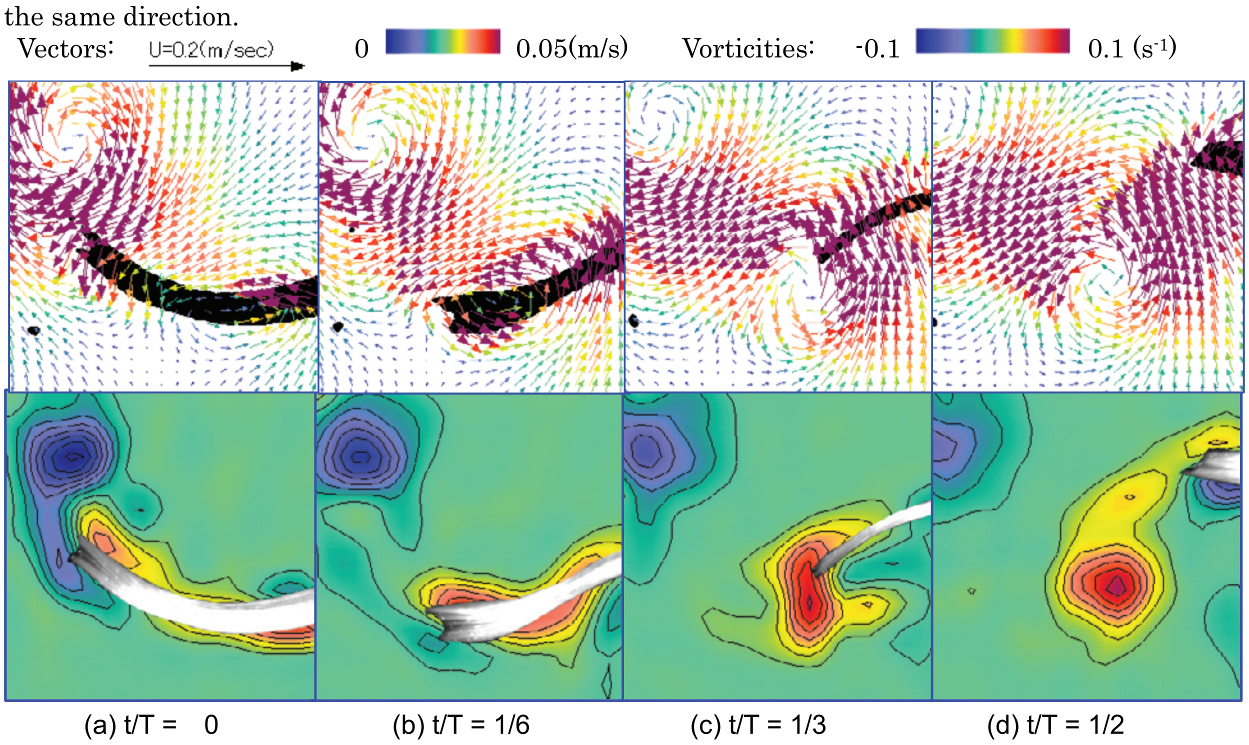


Fig. 11. Loach and vortex interactions around the caudal fin（Vector plots and Vorticity plots）.

The fin is flexible and we can see the shape changes from Fig. 11(a) to (d) by shaking. Possibly the fin is bent by the fluid and its inertial force. We can also guess that the fin is twisted along the body axis from Fig. 11. Figure 12 is additional observation of the back view in deep water and we can see the caudal fin inclines. Thus when the loach shakes fin, it bends and twists the fin at the same time.

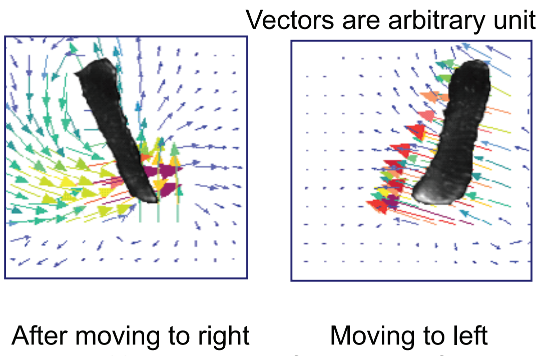


Fig. 12. Back view of the caudal fin.

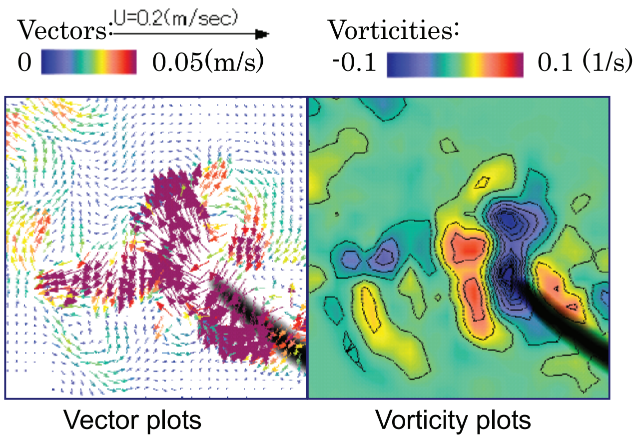


Fig. 13. Flow field without the caudal fin.

If without the caudal fin what will happen? Here the role of the caudal fin is studied comparing the flow field with or without the caudal fin. Vector and vorticity plots without the caudal fin are shown in Fig. 13. In both of vector plots and vorticity plots, small vortices are scattered without the caudal fin, while large vortex is formed with the caudal fin. Without the caudal fin the loach can not form a large vortex. The swimming speed without the caudal fin is decreased about to a half compared to that with the caudal fin. Thus forming and releasing a large vortex using the caudal fin may relate to loach propulsion.

As shown, the fin moves to accelerate the vortex rotation during vortex come from the body and leaves from the fin. It means the loach also gain propulsion through the caudal fin which accelerates the vortex rotation. Another point is the vortex may help the fin motion by rotating in the same direction with the fin, or fin uses the vortex to reduce resistance. The caudal fin is flexible and can follow the flow direction change and also can absorb the fluctuations, which seems to make it possible smooth motion and power transmission from the body to the water.

4. Conclusions

Loach has unique propulsion technique bending its long body. Its motion and flow around it have been experimentally investigated by particle image velocimetry (PIV). Vortices around a loach and the interactions between the loach motion and water flow are analyzed. Generating and growing vortices by bending its body, it pushes water backward to gain repulsing force, at the same time it moves through vortices and seems to reduce the resistance force. After moving forward it leaves a vortex street like reverse Karman vortices which means loach gains propulsion. When the caudal fin releases vortices, it accelerates both sides of the vortex pushing water back and gaining propulsion. The vortex rotates in the same direction as the caudal fin motion, which means vortex reduce resistance against the fin motion. To conclude, loach gains propulsion pushing water forming vortices backward by using both of its fin and body and seems to reduce the flow resistance by the flexible body and fin motion utilizing vortices.

Results shown here are idealized 2D-flow field in shallow water. It is useful to discuss 2Dphenomena, but real flow in nature is 3D flow with vertical vortex. Experiment of 3D flow is underway. The authors appreciate Mr. Shinohara for his help in the experiments.

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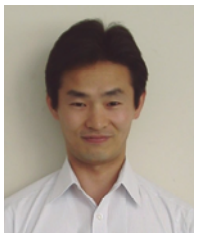

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