Investigation of the propulsion mechanism of swimming killifish

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There have been some investigations of acceleration of a fish from start to terminal state, and dependence of fish shape, Reynolds number and so on has been discussed in previous studies[1,2]. The present paper discusses evaluation of thrust and drag of a swimming killifish-like small fish through three-dimensional simulations using CIP method[3]. Figure 1 shows the shape of the fish covered with triangle meshes for an immersed boundary method[4]. Equation (1) is employed as a function of the wavy lateral oscillation of the midline of the fish.

(a) Lateral view (b) Horizontal cross-section view

Fig. 1 Shape of the fish

$$h(x,t) = f(x) \bullet \sin\left(\frac{2\pi}{\lambda}(x-\lambda f t)\right), \quad f(x) = 0.02 - \frac{33}{400}X + \frac{13}{80}X^2, \quad (1)$$

where $X = x - x_0 \left(0 \le X \le 1\right)$, x_0 is the x-coordinate of fish head and $\lambda = f = 1.0$.

A non-inertial Cartesian coordinate in which the accelerating fish is fixed in the computational frame is applied. Hence, the dimensionless incompressible Navier-Stokes equations for the frame and the Newton's law for translational speed of the fish $\mathbf{U}_c(t) = (U(t), 0, 0)$ can be described as follows[5,6]:

$$\frac{\partial \mathbf{u}'}{\partial t} + (\mathbf{u}' \cdot \nabla)\mathbf{u}' = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2 \mathbf{u}' + \mathbf{G}' - \frac{d\mathbf{U}_c}{dt}, \quad \nabla \cdot \mathbf{u}' = 0, \quad V\frac{dU(t)}{dt} = \frac{1}{2}C_D, \quad (2)$$

where $\mathbf{u}' = \mathbf{u} - \mathbf{U}_c$ is the flow velocity in the frame, $\mathbf{G}'$ is the additional force for the immersed boundary method and V is the dimensionless volume of the fish, assuming the density of fish is the same as the one of fluid. A reference speed is $c_0 = Lf_0$ where L and f_0 are the fish length and a frequency; for example, $L = 7.0\,\mathrm{cm}$ and $f_0 = 1.0\,\mathrm{Hz}$ in water for Reynolds number $\mathrm{Re} \equiv L^2 f_0 / \nu \cong 5000$. Here, Re changes from 300 to 12000.

Figure 2(a) and (b) displays snapshots of vortex structure represented by isosurface of second invariant for Re=1000 and 9000, respectively. Propagating vortex behind the fish remains for large Re, while vortex immediately diffuses due to the viscocity for small Re. Hence, the fish for large Re is considered to be accelerated fast by similar mechanism to two-dimensional reversed Karman vortex.

Next, we assume the right-hand side of Newton's law is described as free fall as follows[5,6]:

$$V\frac{dU(t)}{dt}=\frac{1}{2}C_D=A-BU(t)\;\Rightarrow\;U(t)_{ex}=\frac{A}{B}\left(1-\exp\left(-\frac{B}{V}t\right)\right),\quad(3)$$

where unknown parameters A and B will be estimated so that $U(t)_{ex}$ in Eq. (3) can interpolate simulation results of fish speed $U(t)_{num}$; A and BU correspond to thrust and drag, respectively.

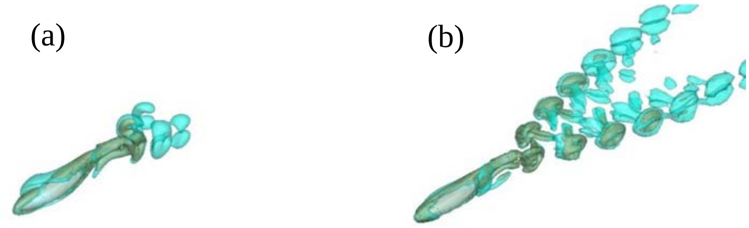

Fig.2 Vortex structure (a)Re=1000, (b)Re=9000

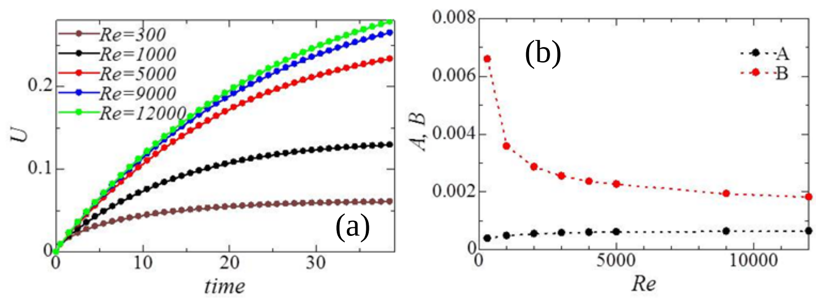

Fig.3 Dependence of Re on (a)fish speed and (b)coefficients (A, B)

Figure 3(a) and (b) shows dependence of Re on time variation of fish speed U and coefficients (A, B), respectively. Dots and solid lines in Fig. 3(a) are $U(t)_{num}$ and $U(t)_{ex}$, respectively; $U(t)_{num}$ is the mean speed in a motion period. Figure 3(a) has indicated that a fish can be accelerated fast for large Re, and $U(t)_{ex}$ with suitable coefficients (A, B) can estimate simulation results $U(t)_{num}$ very well. It is found in Fig. 3(b) that the coefficient A is almost independent of Re, while the B decreases and becomes an asymptotic value with increasing Re. The constant A is thought to come from pressure field around a deforming body, then, coefficient A will depend on shape and motion of a fish. One of our future plan is to estimate thrust/drag and propulsive efficiency of a fish with real motions using visualizations as well as simulations.

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