The swimming patterns and energy-saving mechanism revealed from three fish in a school

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ABSTRACT

Fish in nature are believed to favor their swimming performance by swimming in a school. We investigated numerically the thrust and power consumption of a school of fish with an arrangement of one upstream and two downstream. The upstream fish enhances the thrust with an area of high pressure at the heads of the two downstream fish, but the region of low pressure created between the two downstream fish generates a strong suction and is detrimental to the swimming of the upstream fish. The thrust forces increase but the power consumptions of the downstream fish decrease. The downstream fish in this arrangement can avoid the jet flow of the upstream fish and benefit from the counter flow at the verge of the upstream wake. The power-saving mechanism is obvious and sensitive to the longitudinal distance when the fish are in a school within a small lateral distance. The maximum average power consumption in a school is 20% less than not in a school. The mechanisms of thrust enhancement and energy saving in a school of fish interact in manifold ways, and provide insight into the bio-inspired design for arrays of underwater vehicles.

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1. Introduction

Fish swim by flapping fins or undulating their bodies to transfer the kinetic energy to the surrounding fluid, and are subject to loss of energy because the density and viscosity of water are greater than of air (Webb, 1988). A slender body with a smooth surface found in most modern fish is believed to decrease the drag during swimming. Morphological or behavioral characteristics found among fish have been proposed for their adaptation and energy economy for varied fluid environments (Herskin and Steffensen, 1998; Liao, 2007). Energy-saving strategies found in fish have thus received increased attention in relation to the design of energy-efficient underwater devices.

Fish gain thrust either by undulation of the body-caudal fin (BCF), or by flapping the median-paired fin (MPF). In either case, the structure of vortices revealed in previous numerical or empirical work indicated that hydrodynamic interactions among the flapping fins and the undulating body affect a fish's swimming performance. The suction from the shed pectoral-fin vortices drifting downstream might enhance the lateral movements of the fish body, which leads to power consumption decreased and

efficiency of swimming increased (Ting and Yang, 2009; Lauder and Drucker, 2004; Yu et al., 2011). In tuna, the vortices shed by the motion of the dorsal fin and the tail were observed to produce interference interactions (Zhu et al., 2002). When constructive interference occurred, i.e. the same rotational sign of the vortices generated by the dorsal fin and the caudal fin, thrust was increased, whereas, when the vortices shed by the dorsal fin showed rotational signs opposite to those of the tail-generated vortices, the strength of the wake decreased. From an energetic perspective, this phenomenon can be considered as energy recycling, according to which the undulating body captures the energy from the fin-generated wake.

Swimming fish can not only recycle energy from self-shed vortices but also use varied behavioral strategies to exploit effectively the environmental vortices to increase their swimming performance (Weihs, 1973). For example, Liao et al., (2003) showed that a rainbow trout would perform a special gait to hold its station behind a semi-cylindrical obstacle, shuttling through the Kármán vortices shed by the semi-cylinder presumably to capture the energy from the vortices. Electromyography (EMG) recorded a muscle activity during vortex exploitation less than that of the activity of fish swimming in the free stream, indicating a decrease in the cost of locomotion.

Many fish interact with each other by swimming in schools. Several functional speculations about fish schooling have been proposed, such as predator avoidance, foraging advantage and

social interaction (Abrahams and Colgan, 1985; Partridge et al., 1983; Larsson, 2012). Weihs (1973) examined the hydrodynamic aspect of fish schooling and suggested that the diamond-shaped pattern was the optimal configuration of schooling to gain hydrodynamic advantages. He claimed that, in such an arrangement, the downstream followers could benefit from the reversed Kármán vortex street generated by the upstream fish to decrease the relative velocity beside their body surface that consequently improves their swimming performance. This energy-saving hypothesis for fish schooling has been assessed in the laboratory on comparing the swimming behavior (e.g. frequency of tail beating) and metabolic performance (e.g. consumption of oxygen) of fish at various positions in the school. The fish swimming at the front of a school has generally a greater frequency of tail beating than those at the rear (Herskin and Steffensen, 1998). At greater flow speeds, fish with less metabolic profile tend to swim near the rear of a school but can still maintain the speed with fewer tail beats, indicating that posterior positions provide hydrodynamic benefits that decrease the cost of swimming (Killen et al., 2012).

To investigate the details of the flow structure around each fish, computational fluid dynamics (CFD) has been widely applied to analyze the hydrodynamic interactions and force performance of fish swimming in varied arrangements (Dong and Lu, 2007; Deng and Shao, 2006; Deng et al., 2007; Hemelrijk et al., 2014). Dong and Lu, 2007 investigated numerically the channeling effect that ensues from two traveling foils arranged side by side. This channeling creates a region of low pressure between two parallel fish in which the fluid is accelerated when it passes through. Those authors predicted that the fish prefer to make the undulating body motions in phase to save swimming energy. From comprehensive research, Hemelrijk et al. (2014) argued that the interactions between water and fish enhance the forward movement in a school of fish in more ways than previously considered. The sideways movement of the head of a following fish also plays an important role when fish are swimming in a school. According to their findings, swimming in a school is nearly invariably more efficient than swimming alone, even in a line or rectangular configuration. To simulate self-propelled swimmers, Gazzola et al. (2014) presented a numerical method with a learning algorithm; with that algorithm in their model, the swimmers can learn to adapt their motion, which is similar to the functions of fish in a lateral line. They found that the swimming trajectories diverge when the swimmers swim parallel; the trajectories maintain linear for swimmers in a V-shape. Daghooghi and Borazjani (2015) investigated the fish swimming in a school in rectangular patterns; their fish model was considered to be three-dimensional (3-D) and to involve self-propulsion. Their results indicate that the fish in a school with a smaller lateral distance can swim more rapidly than fish swimming alone; the fish can hence swim longer with the same power consumption when in a school. The authors attributed the enhanced swimming speed to a channeling effect instead of a vortex hypothesis, as there is no significant interaction between the fish and the upstream wake observed in a 3-D fish school. The intricate mechanisms to save energy in varied schooling arrangements are still unclear, especially from the point of view of hydrodynamics.

In this work, we conducted numerical simulation to examine the thrust enhancement and energy saving of three stably swimming fish with only one fish upstream and two fish downstream. The complicated interactions among the fish were investigated on controlling their longitudinal and lateral distances. The thrust production and power consumption of each fish were analyzed and are discussed in a context of flow fields to demonstrate the hydrodynamic interactions between the shedding vortices and the undulations of the fish body. The mechanisms of thrust enhancement and energy saving of fish schooling that we propose provide

a biomechanical foundation for the design of a formation of underwater vehicles to achieve a minimized cost of energy.

2. Research method

To associate the results with empirical data on Tinfoil Barbs, we performed a numerical simulation of carangiform fish swimming in a school, employing the same method of numerical modeling as in our previous work (Yu et al., 2013). The two-dimensional model of a fish body was based on the profile of a NACA0012 foil; the fish were arranged as in Fig. 1 in which L represents the length of the fish and U the free-stream velocity. We set a large distance ($11L$) between a fish and the wall to minimize the wall effect on the fluid field around the fish. The lateral distance between the upstream fish and downstream fish is D; the longitudinal distance between the two downstream fish is S. The undulation of the fish body was simplified as a wave function (Hemelrijk et al., 2014; Liu and Kawachi, 1999; Reid et al., 2012; Yu et al., 2013), described as

$$y\left(\frac{x}{L}, t\right) = a\left(\frac{x}{L}\right)\sin\left[2\pi\left(\frac{x}{\lambda} - ft\right)\right] \tag{1}$$

in which appear time t, wavelength λ and frequency f of fish undulation. Body length L of a fish was set at 10 cm. In most fish swimming with carangiform locomotion, the wave length is observed in a range $0.89 \sim 1.10L$; λ was hence taken as the body length (L) in all simulations. Amplitude envelope $a(x)$ of the lateral motion of the body wave (as shown in Fig. 2) is approximated with a quadratic form (Yu et al., 2013),

$$a\left(\frac{x}{L}\right) = 0.002 - 0.12\left(\frac{x}{L}\right) + 2\left(\frac{x}{L}\right)^2, \tag{2}$$

The governing equations are the two-dimensional viscous incompressible continuity equation and Navier–Stokes equation,

$$\nabla\cdot\vec{u} = 0 \tag{3}$$

$$\frac{\partial\vec{u}}{\partial t} + (\vec{u} - \vec{u}_g)\cdot\nabla\vec{u} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\vec{u} \tag{4}$$

in which $\vec{u}$ denotes the velocity vector, $\vec{u}_f$ the fluid velocity vector, and $\vec{u}_g$ the mesh-grid velocity vector; ρ denotes density, υ kinematic viscosity, and p pressure (Sheu and Chen, 2007). The governing equations were discretized with a finite-volume method. The discrete time and space were solved with an Euler scheme and a second-order upwind scheme respectively. The simulation of the motion of a fish swimming in a fluid is a complicated transient-moving boundary simulation; the time discretization is hence a critical challenge. Although the temporal accuracy of the Euler scheme is only first order, it can avoid optimally a divergence of the numerical computation. We chose a small time step to approximate a more accurate numerical solution. The simulations were solved with commercial software (CFD-RC, France) applying the SIMPLEC algorithm. The space discretization of the computational domain was accomplished with a block-structured mesh; the mesh refinement was used on the boundary layer near the fish body and in the wake-forming region. The Strouhal number, defined as $St = fL/U$, was set at 0.3 to improve the swimming performance (Triantafyllou et al., 2000); the Reynolds number, defined as $Re = \rho UL/\mu$, was set at 1.2×10^4. The thrust force and drag force are almost balanced within a cycle under these swimming conditions, which are similar to the conditions of stable forward swimming of real fish. To explore the energy-saving mechanisms of a school of fish, we examined the hydrodynamic interactions between the members of the school with varied distance apart,