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Numerical Simulation of a Three-Dimensional Fish-like Body Swimming with Finlets

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Abstract. The swimming of a 3D fish-like body with finlets is numerically investigated at Re = 1000 (the Reynolds number is based on the uniform upstream flow and the length of the fish-like body). The finlets are simply modeled as thin rigid rectangular plates that undulate with the body. The wake structures and the flow around the caudal peduncle are studied. The finlets redirect the local flow across the caudal peduncle but the vortical structures in the wake are almost not affected by the finlets. Improvement of hydrodynamic performance has not been found in the simulation based on this simple model. The present numerical result is in agreement with that of the work of Nauen and Lauder [J. Exp. Biol., 204 (2001), pp. 2251-2263] and partially supports the hypothesis of Webb [Bull. Fish. Res. Bd. Can., 190 (1975), pp. 1-159].

AMS subject classifications: 76D05, 76Z10, 76D17

Key words: Finlets, fish swimming, Immersed Boundary method, wake structure.

1 Introduction

The high performance of fish locomotion has attracted the attention of both biologists and engineers for a long time. The hydrodynamic efficiency and maneuverability have been the subject of numerous studies. For example, Bainbridge [1] studied the relationship of body length, tail beat frequency and swimming speed; Wu [2] used the two-dimensional undulating plate theory to predict the swimming performance; and Lighthill [3] extended the three-dimensional slender-body theory to calculate the hydrodynamics. Recently, Zhu et al. [4] studied the three-dimensional flow structures and vorticity control using a fish-like model and nonlinear inviscid flow method. Zhang et al. [5] investigated experimentally the interaction of a deformable filament (a passively swimming fish) with the surrounding flows. Later, Zhu and Peskin [6] performed a numerical simulation based on

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the experiment of Zhang et al. [5]. Lauder et al. [7] analyzed the pectoral fin swimming in sunfish experimentally. Dong et al. [8] quantitatively characterized the propulsive performance of the pectoral fin using numerical simulation. A recent review on fish swimming was given by Bandyopadhyay [9]. Compared with experimental study, numerical simulation has some advantages in control of fish-body kinematics and availability of data for the entire flow field. Thus it is playing a more and more important role in studying fish swimming, especially the role of appendages, such as dorsal fin, anal fin and pelvic fin etc. In this paper, the role of finlets is investigated using numerical simulations.

Finlets are small non-retractable fins located on the body margins between the dorsal/anal fins and the caudal fins [10]. The fish with finlets usually is capable of performing high-performance locomotion, such as mackerel, tuna and bonito. Some of the finlets are rigid and flat, while others are flexible. The total surface area of the finlets can reach 15% of the caudal fin.

Because of the special position and the relatively large area proportion of the finlets, it is suspected that the finlets play a role in fish locomotion. Walters [11] proposed that the finlets direct flow longitudinally along the body and prevent rolling; while Webb [12] and Lindsey [13] proposed that the motion of the finlets can reduce the drag in swimming by preventing the separation of the boundary layer. Nauen and Lauder [14] studied the flow around the caudal peduncle and finlets of the chub mackerel scomber japonics, and claimed that the finlets have a hydrodynamic effect on local flow. Bandyopadhyay [9] postulated that the finlets enhance the main thrust jet by producing a pair of counter-rotating vortices with an intervening jet converging toward the tail. To summarize, the role of finlets is still controversial.

In order to investigate the role of finlets, the present work numerically simulates the swimming of a three-dimensional fish-like body with and without finlets. The finlets are modeled as continuous thin rigid plates attached to the contraction region of the dorsal and ventral ridges. The finlets undergo undulation with the body. With this finlets model, the results of the present work indicate that the finlets direct the local flow around the caudal peduncle, but have little effect on wake structures. This result partially supports the hypothesis of Webb [12] and Lindsey [13], and is in agreement with the work of Nauen and Lauder [14]. However, the finlets model used in the present work is different from the morphology of a real fish. To further verify this hypothesis, simulation based on the geometries and kinematics of real fish will be performed in the future work.

This paper is organized as follows. The numerical model and method are given in Section 2. The numerical observations and discussions are presented in Section 3. Finally, conclusions are drawn in Section 4.

2 Numerical model and method

2.1 Numerical model

In the present work, we consider a fish-like body undergoing prescribed undulation in a uniform flow. The unsteady three-dimensional incompressible Navier-Stokes equations