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Letter

Numerical simulation of the self-propulsive motion of a fishlike swimming foil using the δ^{+}-SPH model

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ABSTRACT

The present work is dedicated to the application of the recently developed (δ^{+}-SPH) scheme to the self-propulsive fishlike swimming hydrodynamics. In the numerical method, a particle shifting technique (PST) is implemented in the framework of δ-SPH, combining with an adaptive particle refinement (APR) which is a numerical technique adopted to refine the particle resolution in the local region and de-refine particles outside that region. This comes into being the so-called δ^{+}-SPH scheme which contributes to higher numerical accuracy and efficiency. In the fishlike swimming modeling, a NACA0012 profile is controlled to perform a wavy motion mimicking the fish swimming in water. Thanks to the mesh-free characteristic of SPH method, the NACA0012 profile can undergo a wavy motion with large amplitude and move forward freely, avoiding the problem of mesh distortion. A parallel staggered algorithm is adopted to perform the fluid-structure interaction between the foil and the surrounding fluid. Two different approaches are adopted for the fishlike swimming problem. In Approach 1, the foil is fixed and flaps in a free stream and in Approach 2, the wavy foil can move forward under the self-driving force. The numerical results clearly demonstrate the capability of the δ^{+}-SPH scheme in modeling such kind of self-propulsive fishlike swimming problems.

Fishes are very smart swimmers in water. Fishes are able to make full use of the flows around their bodies, saving forces, and obtaining the optimal hydrodynamic performance [1]. So far the man-made underwater vehicle is very difficult to swim in such a high efficiency like a fish. Humans still need to learn a lot form animals.

Fishlike swimming has been a classic hydrodynamic problem which attracts the attention of researchers for a long history [2–5]). Many works has been done, trying to explain the mechanism of swimming propulsion of single fish [6–8] and the reason of fish schooling [5, 9, 10]. The fishlike swimming problem also has many applications in the field of naval architecture and ocean engineering. One remarkable application is in the propulsion of marine vehicles. The swimming propulsion or bionic propulsion can have higher efficiency than the using of screw propeller and can avoid the problem of hydroacoustic noise and cavitation erosion. Recently, with the rapid development in the research of underwater vehicles, many of them are designed to have a fishlike shape, use a swimming propulsion and therefore have superior stealth property.

In the early years, the study of fishlike swimming hydrodynamics are mainly based on experimental observations [3]. Recently as the development of the computational fluid dynamics (CFD), the investigations based on the numerical models are also rapidly growing. One representative numerical method is the immersed boundary method (IBM) which uses a Lagrangian boundary to track the surface of the rigid or deformable structure with complex shapes [11]. With the hybrid of IBM and other

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Naiver–Stocks solvers, fishlike swimming problems have been modeled for both two dimensional (2D) [9, 10, 12] and three dimensional (3D) cases [13].

To the best of our knowledge, there are still very few publish papers modeling fishlike swimming problems using mesh-free or particle methods. One of the most widely used particle methods in the study of fluid dynamics is the smoothed particle hydrodynamics (SPH) method [14, 15]. Similar to IBM method, SPH also has the advantage of solving fluid-structure interaction (FSI) problems characterized by moving boundaries with large deformations [16].

In the traditional works, when investigating the self-propulsive swimming bodies, the swimmers are fixed in an uniform incoming free stream with a fixed inflow velocity U. The hydrodynamic forces on the swimming body are measured. When the streamwise force becomes negative, the fish is considered to be able to swim forward with a speed larger than the inflow velocity U. This investigation method is named as Approach 1 in this work. Approach 1 has been adopted in Deng et al. [9] and Dong and Lu [10] to study the hydrodynamic performance of a single fish and the interactions between two fishes in different relative locations. However, strictly speaking, the hydrodynamic state of the flapping fish fixed in a stream is different to the one swimming freely in the still fluid (Approach 2). In the former case, the fish is constrained by a varying external force to make it remain in its location, while in the latter case, the fish stays in a situation that the propulsive force, drag force, and inertia force reach a dynamic balance.

The theoretical model of the real self-propulsion under Newton's law has been proposed from the end of last century by Carling et al. [17]. In that work, 2D anguilliform swimming was modeled using the finite difference method (FEM) and advantages of allowing for acceleration and deceleration of the swimmer's body were demonstrated. Yang et al. [12] extended the theoretical model of Carling et al. [17] and 2D simulations in the framework of finite volume method (FVM) were performed. This model has been further extended into 3D problems regarding the fast-start swimming and fish's body-shape optimization by Xin and Wu [18, 19].

In the present work, Yang's self-propulsion model [12] has been applied in the framework of a particle method. The recently developed δ^+-SPH model [20] is adopted to model the self-propulsive fishlike swimming problem and investigate the speedability of the swimming foil with different flapping parameters. In order to understand the mechanism of the thrust force generated in different swimming conditions, the vortical structures in the flow field can be detected by Eulerian definitions, e.g. vorticity or Q criterion. Finite-time Lyapunov exponent (FTLE), which is a Lagrangian definition used to reveal Lagrangian coherent structures (LCSs), can also be calculated and it helps understanding the flow physics in a Lagrangian way [21]. Recently, 3D LCSs have been reveled by Kumar et al. [22] in the FTLE field and the latter has been shown to be a reliable tool to study the relationship between the thrust generation and the wake structure behind a pitching panel. As emphasized in Ref. [23], the Lagrangian nature of SPH method provides greater convenience than the Eulerian CFD solver in detecting LCSs through the calculation of FTLE field.

Similar to Deng et al. [9], Dong and Lu [10], and Yang et al. [12], a NACA0012 foil is adopted to mimic the backbone undulation of a swimming fish. The midline of the NACA0012 foil is designed to undulate according to the following formula:

$$y'(x',t) = A(x')\cos(kx' - 2\pi f t + \phi), \quad 0 \le x' \le L, \tag{1}$$

where y' is the vertical oscillating magnitude and x' is the local horizontal coordinate starting form the foil head to the tail and therefore we have $0 \le x' \le L$ where L is the length of the foil. The wave number is $k = 2\pi/\lambda$ where the wave length λ is equal to L unless otherwise specified. The streamwise travelling wave propagates with a constant phase speed as $c_p = 2\pi f/k$. ϕ is the phase angle of the wavy foil. $A(x')$ is the oscillating amplitude depending on the local horizontal coordinate on the foil. $A(x')$ is usually determined by the swimming characters of different fishes [24].

Generally two approaches can be adopted to investigate the hydrodynamic performance of swimming bodies. In Approach 1, the swimming body flaps in a free stream but its location is constrained on a fixed position by an external force, see the left part of Fig. 1. The free stream with a steady velocity of U enters from the left side of the fluid domain. The fluid domain is designed with the width of $6L$ in order to avoid the blockage effect from the lateral walls on which a free-slip boundary condition is imposed. The fish is placed $3L$ away from the in-flow boundary and the total length of the fluid domain is $12L$ which is large enough to avoid the effect of the out-flow boundary. The hydrodynamic force on the swimming body is measured and if the drag force coefficient is negative, it means the swimmer can move forward with a speed larger than the inflow velocity U.

In Approach 2, the swimming foil is able to move forward under the thrust force, see the right sketch in Fig. 1. According to

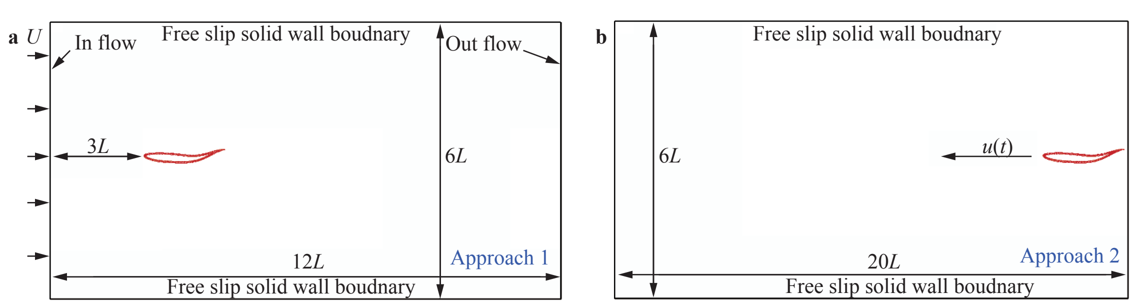

Fig. 1. Sketches for the fluid domain and the placement of the fishlike swimming foil in different investigation approaches. Plot **a** shows the concept of Approach 1, where the fish is fixed in an incoming free stream; plot **b** shows the concept of Approach 2, in which the fish is self-driven to swim forward in a still fluid field.