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Numerical study of the thunniform mode of fish swimming with different Reynolds number and caudal fin shape

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ABSTRACT

The hydrodynamics of a model-fish swimming in thunniform mode was studied numerically in this paper. A 'tuna'-like configuration and the undulating manner (the kinetics of swimming) were adopted from some references. The unsteady incompressible RANS equations were solved by an unsteady flow solver based on dynamic hybrid grids, which was developed by the authors in previous work. During the simulations, two typical turbulence models (SA-model and SST-model) were employed to investigate the turbulence effect, and compared with the 'laminar' case (switch off the turbulence models). The influence of Reynolds number was studied also. Numerical results demonstrate that the propulsion performance is better when considering turbulence models at higher Reynolds number, because the flow separation is relatively weaker than the 'laminar' cases. Furthermore, three types of caudal fin models were considered emphatically, including the popular crescent-shaped fin, a semicircle-shaped fin and a fan-shaped fin. Numerical results show that the crescent-shaped caudal fin is the most efficient when cruising, although the 'thrust' is relatively less. The main reason is that the energy loss in the lateral direction is less than those of the other two caudal fin models.

1. Introduction

As the most popular aquatic animals, all fishes have excellent swimming ability to adapt the aquatic environment. Their geometry and locomotion manner was hypothesized to be optimized because of the evolution of billions of years. The comparative biomechanics and physiology of moving through water has long attracted the attention of both biologists and engineers, and recent decades have witnessed considerable growth in the study of aquatic animal locomotion. Major results of these efforts include a much more complete understanding of how fish swimming in the water use their muscles to power movement, detailed descriptions of body and appendage motion during propulsion, and experimental and computational analyses of fluid movement and the attendant forces (for reviews, see Refs. [1–6]).

Different fishes swim in different ways. To categorize this diversity, fish swimming is usually classified into a variety of different modes, such as anguilliform, subcarangiform, carangiform, thunniform and ostraciiform. As the most swift and efficient mode of BCF(Body and Caudal Fin) mode, the thunniform mode is adopted by some large-scale fishes, such as shark and tunny. Within the thunniform mode, the swing of body is relatively small, but the caudal fin stroking left and right (or up and down for whales) to generate sufficient power for swimming. Therefore, the area and configuration of the caudal fin must be very important for their swimming ability.

Many scientists had studied the configuration and the undulating manner of fish to investigate the mechanism for swimming and maneuvering [7–15]. Experimental as well as numerical results had shown that the 'reversed *Karman* vortex street' can be gained in the wake of a swimming fish. This 'reversed *Karman* vortex street' which induces a jet-flow plays the central role for 'thrust' generation. Further research by Triantafyllou and Triantafyllou [10] denoted that the vortices form optimally when the *Strouhal* number lies between 0.25 and 0.35, the swimming of fishes would be very efficient. Because of the different geometry and the undulating manner, the wake flow for various fishes must be different from each other. Therefore, various fishes have different swimming ability. Early in 1970s, Webb analyzed the relationship between the configuration and the swimming ability theoretically [8]. In 2007, Zhao et al. [14] studied the 'C-start' of a fish and found that the 'thrust' is proportional to the product of its area and dimensionless second-moment of the caudal fin, and this conclusion was validated experimentally by Li and Yin [15] in 2008. However, because of the variety of fish, further studies are needed to discover their hydrodynamic mechanisms.

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In this paper, a tuna-like fish is modeled firstly based on the model of the *RoboTuna* in Ref. [16]. The unsteady incompressible RANS equations are solved by an unsteady flow solver based on the moving hybrid grids, which was developed by the authors in previous work [17]. In real-life fish swimming, the fish is self-propelled, and the unsteady flow solver should couple with the movement equations (the six degrees of freedom movement equations) and proper control law. The flow physics and mechanism will be so complicated if considering this coupled movement. To focus the study on propulsion mechanism, the straight-line cruising assumption is introduced in this paper, which means that the fish is cruising in a mean flow. So the coordinate system can be transferred into the body-fixed system using the *Galilean* transformation. During the simulations, two typical turbulence models (SA-model and SST-model) are employed to investigate the turbulence effect, and compared with the cases without turbulence models (named as the 'laminar' cases in the following context, marked as 'LAM' in the figures). The influence of Reynolds number is studied also. Numerical results show that the propulsion efficiency increases with the Reynolds number increasing. Comparing with the 'laminar' cases, the propulsion efficiency for the turbulence cases is relatively higher. Furthermore, three kinds of caudal fin models are investigated to study the hydrodynamic mechanism of the thunniform mode swimming, including the most popular crescent-shaped fin, a semicircle-shaped fin and a fan-shaped fin. Numerical results show that the biggest fan-shaped caudal fin can generate more thrust than the other two models. However, the energy (or power) consumption is the least for the popular crescent-shaped tail when cruising, which means that the crescent-shaped tail is the most efficient with the undulating manner adopted in this paper.

2. Geometry of fish model and kinetics of swimming

As mentioned in the introduction, we only consider the straight-line cruising with a constant speed U (in the X-direction). So we can apply two coordinate systems in the study: an inertial global coordinate system $OXYZ$, fixed in space, and a local coordinate system $oxyz$, instantaneously fixed on the flexible body and orthonormal to the stretched-straight mean line and body section plane. The relation between the body-fixed coordinate system $oxyz$ and the global coordinate system $OXYZ$ is $x = X + Ut$, $y = Y$ and $z = Z$, where t is the time. So here, the well-known *Galilean* transformation is employed in the following study, which means the simulations are carried out in the body-fixed $oxyz$ coordinate system.

2.1. Geometry of fish model

In the present work, we employ body shape representing a tuna to study the flow structure around three-dimensional flexible bodies undergoing fish-like swimming. The geometry of the *RoboTuna*, a laboratory robot [16], is employed to emulate the body shape and motion. The similar model has been employed in Refs. [18,19]. A real-life tuna is shown in Fig. 1A. To simplify the simulation, the finlets (the paired and median fins, the dorsal and anal fins) is not considered in this study. So the fish model composites two main parts, the body and the caudal fin. The body is simplified as a spindle shape and the length of the body (from the head to the peduncle, without the caudal fin) is 1.0 m. In this paper, the length of fish body (L = 1.0 m) is taken as the reference length. To simplify the simulation, we make an assumption that the object is an elongated body with body length unchanged during swimming. Using curve fitting to describe the shape of the *RoboTuna*, the profile of the body is given as

$$\begin{cases} y(x) = \pm 0.152\tanh(6x + 1.8) & \text{for } -0.3 \leqslant x \leqslant 0.1 \\ y(x) = \pm[0.075 - 0.076\tanh(7x - 3.15)] & \text{for } 0.1 < x \leqslant 0.7 \end{cases} \tag{1}$$

At each horizontal position x, the body sections are assumed to be elliptical with a major-to-minor ratio of $AR = 1.5$, where the major axis corresponds to the height of the body (in the y direction).

The caudal fin has chordwise sections of NACA 0016 shape. The leading edge and trailing edge profiles $x(y)_{LE}$ and $x(y)_{TE}$ are also determined through a curve fitting technique, and are given by

$$\left.\begin{cases} x(y)_{LE} = 39.543|y|^3 - 3.585|y|^2 + 0.636|y| + 0.7 \\ x(y)_{TE} = -40.74|y|^3 + 9.666|y|^2 + 0.77 \end{cases}\right. \quad \text{for } -0.15 < y < 0.15 \tag{2}$$

The configuration of the base model (Model-1) introduced above is shown in Fig. 1B. For the thunniform mode swimming, the caudal fin is primary for thrust generation. Therefore, the shape and motion of caudal fin is important for their swimming ability. In order to study the mechanism for thrust by the caudal fin shape, two other models of the caudal fin are introduced also in this paper, including a semicircle-shaped fin (Model-2 as shown in Fig. 1C) and a fan-shaped fin (Model-3 as shown in Fig. 1D). The trailing edge profile of Model-2 is assumed as a straight line, while the trailing edge profile of Model-3 is assumed as a circle:

$$(x_{TE} - 0.8)^2 + (y)^2 = 0.15811^2 \quad \text{for } -0.15 < y < 0.15 \tag{3}$$

Because of the different tail edge profiles, the chordwise sections of Model-2 and Model-3 should be scaled to get the same thickness as that of Model-1. The geometric parameters of the three tail models are listed in Table 1, in which the dimensionless second-moment area (S_{r2}) and the dimensionless third-moment area (S_{r3}) are defined as follows:

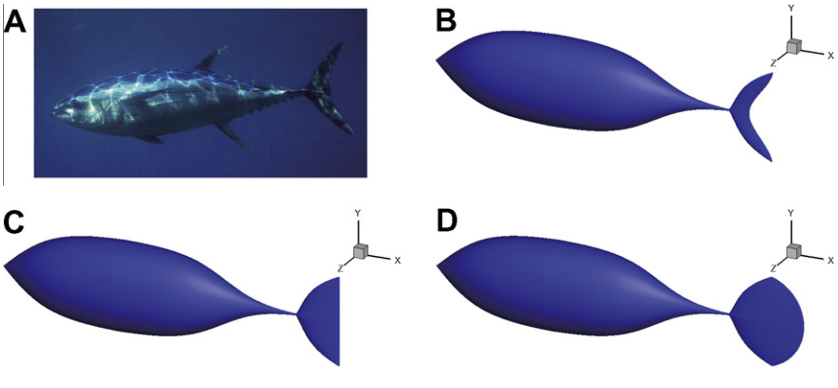

Fig. 1. The shape of body and the three caudal fin models. (A) Real-life tuna; (B) Model-1; (C) Model-2; (D) Model-3.