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The three-dimensional hydrodynamics of thunniform swimming under self-propulsion



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ABSTRACT

This paper presents the hydrodynamics of thunniform swimming under self-propulsion as the body and caudal fin kinematic behaviors are systematically varied. The swimmer is a three-dimensional (3D) tuna-like flexible model with prescribed kinematics of thunniform mode. Simulations are carried out for various body behaviors by varying the wave frequency f and the tail amplitude A_p , and for various caudal fin behaviors by varying the maximum angle of attack α_{\max} and the phase difference φ . The results show that the swimming velocity as well as the propulsive efficiency is an increasing function of both f and A_p , but their trend with α_{\max} and φ is found to be not monotonic. Specially, for peak swimming velocity generation, α_{\max} occurs at 20–30°, and φ ranges from 60° to 75°, while for peak efficiency, α_{\max} is 20–30° and φ nears 90°. The wake structure formed by the swimmer is single row wake consisting of a series of disconnected vortex rings that are resembled by sickle-like shape vortices. As φ increases, the tail of the sickle-shape vortices is shortening gradually while the head is stretching. As α_{\max} increases, the aligned sickle-like vortices have almost identical shape with each other, but the wake strength is reducing gradually.

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1. Introduction

Thunniform swimming is a primary mode of locomotion for numerous fast swimmers. This mode of swimming propels itself forward by propagating traveling wave of the body towards the tail and combining oscillatory motion of the caudal fin, such as juvenile tuna (Lighthill, 1969, 1970; Sfakiotakis et al., 1999; Dewar and Graham, 1994; Donley and Dickson, 2000; Altringham and Shadwick, 2001; Donley et al., 2004). For thunniform swimmer, the large amplitude of undulations is mostly restricted to one-half or even one-third the posterior part of the body, and increases sharply near the caudal area. Beginning with the representative work (Gray, 1933), thunniform swimming has attracted much more scientific attention among biologists and engineers, ranging from bioscience to hydrodynamics, due to its potential for providing artificial systems with advanced propulsor designs (Sfakiotakis et al., 1999; Tytell and Lauder, 2004; Fish and Lauder, 2006; Shadwick and Syme, 2008; Leftwich et al., 2012).

Unfortunately, a number of intriguing aspects regarding this mode of locomotion remain unknown, such as how can the fast swimming speed of a thunniform swimmer be generated by its

body and caudal kinematics? How does the kinematics affect the swimming efficiency and the wake signatures? Such questions motivate more detailed studies about the hydrodynamics for this mode of swimming. For instance, as in nature certain swimmers may increase their tail-beat frequency other than tail-beat amplitude accompanying with the increase of their swimming velocity, i.e. kawakawa tuna displayed a significantly greater frequency but lower amplitude than chub mackerel for achieving a prescribed velocity (Donley and Dickson, 2000). Likewise, the tail-beat frequency was varied systematically while keeping the amplitude constant to achieve a prescribed value of swimming velocity for thunniform swimmer (Barrett, 1996; Shadwick and Syme, 2008). These studies tell us that both the frequency and the amplitude can be applied to realize a specified swimming velocity for this mode of swimming, however, the above questions that actually how the swimming velocity being determined from these two parameters has not been answered either. Correspondingly, the swimming efficiency and the wake signatures associated with various kinematic behaviors are still unclear.

For thunniform swimming, another aspect of kinematics is the detailed characterization of the caudal fin motion, which in certain fishes such as tuna could introduce additional kinematical parameters (Barrett, 1996; Wolfgang et al., 1999; Zhu et al., 2002). These parameters, such as the maximum angle of attack and the phase difference between the motion of the heave and pitch, have

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been considered in an inviscid simulation of tuna swimming (Zhu et al., 2002) and were shown to play an important role in the dynamic interactions of vortices shed by the body and caudal fin. Their work provided new insights into the vorticity dynamics of flow, but was limited by the inviscid assumption and the swimming velocity specified in advance. To our knowledge, the effect of various kinematic behaviors of caudal fin has never been examined for self-propelled thunniform swimming, and therefore it is highly desired to be studied to reveal the flow characteristics.

Many numerical studies involved simulating the flow around aquatic locomotion at a specified constant swimming velocity (Liu et al., 1997; Wolfgang et al., 1999; Zhu et al., 2002; Borazjani and Sotiropoulos, 2008, 2009; Rapo et al., 2009; Yu et al., 2011). These simulations shed valuable insight into the hydrodynamics of fishlike swimming, but were limited by the assumption of constant specified swimming velocity. However, computations based on this assumption miss two crucial phenomena occurring in real swimming state. First, the swimming velocity is seldom constant due to the fact that the mean value of fluid forces acting on the fish is not always zero. Second, the specified swimming velocity is likely to distort the wake structures around the body both qualitatively and quantitatively. To include these details, there were several studies that presented simulations of self-propelled anguilliform swimming, i.e. they did not specify the swimming velocity first but obtained it as a solution (Carling and Williams, 1998; Kern and Koumoutsakos, 2006; Borazjani and Sotiropoulos, 2010; Zhou and Shu, 2011; Borazjani and Daghooghi, 2013; Van Rees et al., 2013). In these studies, the swimming velocity is not prescribed first but is computed based on the iterative fluid forces. For the most part, however, all these numerical studies focused on simulating flow either at a specified constant swimming velocity for thunniform mode or under self-propulsion for other modes of swimming, and as such study solving for the swimming velocity instead of taking it as an input for thunniform swimming has yet to be reported in the literature.

Numerous recent experiments with the particle image velocimetry (PIV) techniques (Muller et al., 1997, 2001; Drucker and Lauder, 2002; Nauen and Lauder, 2002; Tytell and Lauder, 2004; Tytell, 2007; Hultmark et al., 2007; Dewey et al., 2012) had provided a wealth of data in terms of both swimming kinematics and wake structures. However, carrying out controlled experiments of various kinematic behaviors is difficult to perform in a live fish. Another difficulty stems from the inabilities in decomposing the thrust and the drag components from the total fluid forces from experiments alone (Borazjani and Sotiropoulos, 2008, 2009). Even if these difficulties could be overcome in experiments, it would still be challenging to estimate the swimming efficiency (Schultz and Webb, 2002), since obtaining 3D flow measurements around a swimming fish is far from straightforward (Borazjani and Sotiropoulos, 2008, 2009). As pointed out by Tytell, the PIV technique for measuring velocities can only provide measurements on plane not the full space (Tytell, 2007). Meanwhile, the pressure field which is also needed to determine the fluid forces is not easy to measure (Dabiri, 2005). These facts emphasize the difficulties for experiments alone to provide conclusive findings in the controllable thunniform swimming under self-propulsion. Fortunately, such insights can be obtained by combining experimental observations with numerical simulation approaches.

In this study, the numerical simulation of thunniform swimming is conducted with the goal of examining the mechanisms of locomotion in greater detail than is possible in experiments. This work is not intended to reproduce the simulations of Wolfgang et al. (1999) and Zhu et al. (2002) – the simulations reported in this paper are concerned on various kinematic behaviors under self-propulsion that the swimming velocity is not specified first but is computed along with the fluid forces. The computed results

are analyzed to illustrate several important aspects of thunniform swimming. These include the prediction of the swimming velocity, the swimming efficiency and power requirement, and the 3D wake structures for several various kinematic behaviors.

2. Materials and methods

2.1. Problem description

In this work, we employ a tuna model as the virtual swimmer, which is composed of a main body with smooth profile and a high-aspect-ratio caudal fin, while all minor fins are neglected. We consider the fish length that matches that of the juvenile tuna reported in Donley and Dickson (2000). In our simulations, the total length of fish is set to 0.2 m, which is in the range of 0.151–0.255 m reported by Donley and Dickson (2000). The physical model of the fish is shown in Fig. 1. During the swimming process, we consider the swimmer starting from rest to self-propelled steady swimming when the mean axial force acting on the fish is zero.

We choose the kinematics for the fish as used in the experiments by Barrett (1996), which closely emulates that found in nature (Dewar and Graham, 1994; Donley and Dickson, 2000). The specific kinematics used here has two basic components: one is the body undulation defined by a flexible spline curve from the nose to the tail peduncle (see Fig. 2) and the other is the caudal fin motion depicted by a heave and pitch complex motion. In this sense, the spline body, which is responsible for the foil's heave and the foil's own rotation is responsible for its pitch, is treated as a traveling wave with its amplitude increasing from the nose to the tail peduncle that expressed by

$$y_b(x, t) = A(x) \sin(\omega t - kx) \quad (1)$$

where x is the axial position, $y_b(x, t)$ is the lateral excursion at time t , $A(x)$ is the amplitude envelope of the lateral motion, ω is the angular frequency, denoted as $\omega = 2\pi f$, and f is the wave frequency, and k is the wave number, denoted as $k = 2\pi/\lambda$, and λ is the wave length. The λ in all the simulations is specified as $1.25L$, which is in the range of $1.23L$ – $1.29L$ observed in most thunniform swimmers (Dewar and Graham, 1994), and L is the fish total length.

Here we assume that the body length is unchanged during the traveling wave motion and its undulation is purely a lateral motion. To model the body motion closely mimic the typical thunniform swimmer's body motion, the amplitude envelope $A(x)$

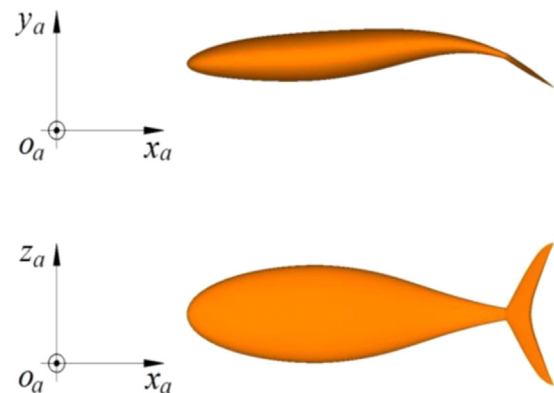


Fig. 1. The thunniform virtual swimmer modeled after a juvenile tuna. The swimmer is composed of a main body and a high-aspect-ratio caudal fin, while all minor fins are neglected. Its swimming coordinate system is defined as follows: x -axis along the fish longitudinal direction to the caudal fin, y -axis along the transverse direction to the right side, z -axis along the spanwise direction, and with the x -axis, y -axis constitutes the right-handed system.

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