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Multi-fin kinematics and hydrodynamics in pufferfish steady swimming

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ABSTRACT

Pufferfish swim and maneuver with a multi-fin system including dorsal, anal, caudal, and pectoral fins, which presents sophisticated ventures in biomimetic designs of underwater vehicles. Distinguished from those 'typical' fish with streamlined body shape and body-caudal fin (BCF) undulations, pufferfish adopt non-streamlined plump body shape and rely on the oscillations and interplay of fins to achieve high performance maneuvering. Aiming at unveiling novel mechanisms associated with multi-fin kinematics and hydrodynamic performance in pufferfish swimming, we carried out an integrated study by combining measurement and digitizing of multi-fin kinematics and three-dimensional deformations and computational fluid dynamic (CFD) modeling of steady swimming. We constructed a realistic multi-fin kinematic model to mimic motions and deformations of the dorsal, anal, and caudal fins. We further built up a CFD model of the pufferfish with a realistic body and multi-fin geometry to evaluate the hydrodynamic performance of its multi-fin system. Our results demonstrate that in pufferfish steady swimming, caudal, dorsal and anal fin rays oscillate while performing significantly passive bending and twist deformations but show a noticeable out-of-phase feature, leading to neutralizing rotational forces and hence suppressing yaw motion, particularly at fast swimming. Numerical simulation suggests that the caudal median fin plays a key role in thrust generation while the dorsal and anal fins also provide a considerable contribution.

1. Introduction

The desire of investigation and exploitations on ocean resources propels the development of underwater vehicles in the past several decades. In nature, fish has superior swimming performance compared to artificial swimmers in many aspects, such as it can achieve fast speed, high efficiency and low noise, presenting sophisticated ventures in biomimetic designs of underwater vehicles. Mimicking the geometric and kinematics of fish is considered as a shortcut to absorb the preponderance of fish swimming into unmanned underwater vehicles (UUV).

Fish swimming modes are generally categorized into BCF (body and caudal fin) and MPF (median and paired fins) modes (Webb and Blake, 1985). BCF mode has good rapidity (e.g. tuna fish), while MPF mode provides good maneuverability. As a subtype of MPF, Tetradontiform swimmers such as pufferfish (Blake, 1983; Webb, 1984, 1994) oscillates pectoral, dorsal and anal fins independently. Those fins coordinate with body-caudal-fin undulation, forming specific gaits depending on the swimming speed. It is observed that pufferfish swim with pectoral, dorsal, anal and caudal fins at lower speed, but at medium-high speed, with the pectoral fins locked coherently attaching onto the body to reduce drag. As an extreme example of Tetradontiform swimmers, boxfish have a rigid body and utilize multi-fins for propulsion and maneuvering (Blake, 1977; Gordon et al., 2000; Walker, 2000; Hove et al., 2001).

Hydrodynamics in fish swimming have been studied through experimental, analytical and computational approaches. Although analytical models, mainly based on elongated-body theory (Fish and Lauder, 2006; Lighthill and Blake, 1990a; Lighthill, 1990b, 1990c, 1990d) that has been widely used, are effective means in studying BCF fish, the swimming with multiple flexible fins and plump body is intractable case for them. Thus, the hydrodynamics of Tetradontiform swimmers are primarily examined through experimental and computational approaches. Recently, hydrodynamics of BCF fish has been studied by experimental observation with PIV (Particle Image Velocimetry) technique, which has been applied to assess fin-based thrust enhancement for MPF swimming in the pufferfish (Wu, 2001; Breder, 1926; Blake and Chan, 2011). Computational fluid

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dynamic (CFD) modeling of hydrodynamics and free-swimming body dynamics that couples the Navier-Stokes (NS) equations to the equations of undulating body motion with pectoral fins has been also developed and employed in unveiling free-swimming hydrodynamics in fish (Liu et al., 1996, 1997, 1999; Liu et al., 2017; Katumata et al., 2009; Li et al., 2011, 2012, 2016).

With respect to the flexible fins in swimming, both passive and active deformation-based control mechanisms have been explored till now for MPF mode (Webb, 2006; Bartol et al., 2005). In the pufferfish swimming, fin and body movements serve in powered control mechanisms, while integumentary ornamentation (e.g., spines) and skin compliance properties are the possible mechanisms for unconscious control (Brainerd, 1994; Gordon et al., 1996; Arreola and Westneat, 1996). However, how fin flexibility influences the hydrodynamics and maneuverability in particular with multi-fin system in pufferfish swimming remains unclear yet.

In this study we aim at unveiling novel mechanisms associated with multi-fin kinematics and hydrodynamic performance in pufferfish steady swimming through an integrated study by combining measurement and digitizing of multi-fin kinematics and three-dimensional deformations and CFD modeling of steady cruising swimming. We first measured the kinematics and deformations of dorsal, anal, and caudal fins with two high-speed cameras by filming a free-swimming pufferfish at specific speeds in circulating water channel. We then digitized and performed a comprehensive analysis of the multi-fin kinematics and deformations in terms of active and passive fin deformations. We further built up a CFD model of the pufferfish with a realistic body and multi-fin geometry to evaluate the hydrodynamic performance of its multi-fin system. Finally we gave an extensive discussion on the effects of flexible fins on multi-fin kinematics and hydrodynamic.

2. Material and methods

2.1. Experimental set-up

2.1.1. Pufferfish and circulating water channel

Pufferfish (*Teleostei: Diodon holocanthus*) were purchased from a local aquarium and kept in a water tank for a week, which had a body length of 11.4 ± 0.2 cm (averaged based on five measurements). Artificial seawater (density: 1.022 ± 0.001 kg·m^{-3}, temperature: 26 ± 2 °C) was used in the water tank. The experiments were conducted in a circulating water channel (Fig. 1) in Jiangsu University of Science and Technology, China. The circulating water channel system was comprised of a water channel, converter pumps and a control cabinet. The working section of the circulating water channel was $50 \times 30 \times 40$ cm (L × W × H). In order to achieve a uniform incoming flow, a rectifying plate was placed in front of the water channel at upstream side. The same artificial seawater was also utilized in the water channel. The rotating speed of the converter pump was controlled by the control cabinet, which successfully achieved a flow velocity range over 0–45 cm/s.

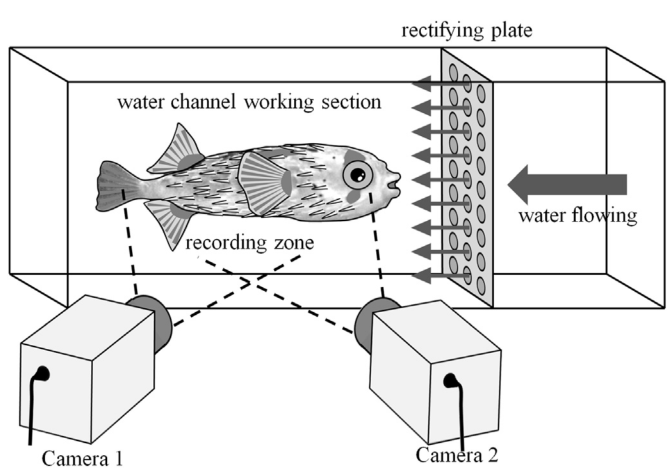

Fig. 1. Sketch of experimental set-up involving the objective pufferfish, a circulating water channel, and a high-speed digital filming system.

2.1.2. High-speed digital filming

In order to record the three-dimensional motions of pufferfish, two high-speed digital cameras were set up in front of the working section of the water channel with a specific angle (Fig. 1). The maximum resolution and frame rate of the cameras (Phantom® Miro® eX4) were 800×600 pixels and 1260 fps, respectively. The two cameras were controlled by a PC computer through data lines and switchboard, which sent commands to achieve synchronous recording of the two cameras with software (PCC 2.4). With a set-up of combining a resolution and a frame rate of 800×600 pixels and 100 fps, the cameras could complete a video recording up to 88 s. The software (PCC 2.4) provided a post-trigger function, which was instrumental in capturing the steady swimming of the pufferfish undergoing free-swimming in the circulating water channel at some given incoming speed.

2.1.3. Calibration of filming

For three-dimensional analysis, calibration was conducted to ensure the calculation of the precise locations of the cameras and to construct the three-dimensional coordinate system. The calibration requires at least 6 discrete points whereas extra points may further increase the accuracy of calibration. Here a calibration fixture was used, which was composed of two sheets with an angle between the two sheets of 120°. Each sheet contained 60 points with an interval (distance) between neighbor points of 2 cm, and that from median line to the nearest points of calibration fixture of 1 cm (Fig. 2). Before recording the pufferfish swimming, the calibration fixture was placed in the working section of the circulating water channel. We confirmed that at least each camera could photograph 20 points on each sheet. The images containing the calibration points were then processed with three-dimensional motion analysis software (ProAnalyst, Xcitex) to reconstruct the three-dimensional Cartesian coordinates (Fig. 2). The validity and accuracy of the calibration fixture was confirmed in advance by measuring the length of a ruler at three different locations, through contrast test and correction, a maximum error of 3.7% of the length was acceptably achieved.

2.1.4. Experiment procedure

In order to adapt the fish to the environment of the experiment, the selected pufferfish were trained to swim freely in the working section of the water tunnel several hours before filming. At the beginning of the experiments, the flow velocity was gradually increased from 0 up to 1.0 L/s, and then the two cameras were turned on synchronously to start filming and recording, which were terminated 5 s after when the pufferfish reached a steady state of swimming. All the filmed video was then transferred and saved to a computer. The same procedure was repeatedly carried out for eleven cases corresponding to different incoming flow speeds ranging over 1.0–3.0 L/s with an interval of 0.2 L/s.

2.2. Kinematic analyses

In order to determine body and multi-fin kinematics, ten stable tail beat cycles with sufficiently high resolution were chosen for the analysis of each case, which were defined as starting from and returning to the maximum (left or right) lateral excursion. The 3D coordinates and cycles selected from the videos were processed with software of ProAnalyst. As illustrated in Fig. 3 we set seven tracking points on the tip and two on the base of caudal, dorsal and anal fins, as well as one frame attached to each fin and one frame of reference attached to the body, respectively. Using reference frame attached to the fish can remove the periodical surge motion caused by the fluctuation of total force exerted on fish during analysis. Note that thirty tracking points *in toto* were set on the body,

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