Bio-inspired Propulsion in Ocean Engineering: Learning from Nature

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ABSTRACT

With multiple fins extending to the surrounding water as their propulsion and maneuvering surfaces, fish exhibit remarkable maneuverability and stability, which has become an important inspiration source to the design of underwater vehicles [1]. Compared with experimental studies with live fish or bio-inspired robotic devices, numerical simulation has the advantages in exploring large parameter matrix, thus providing the detailed fluid flow data and addressing 'what if' problems [2]. Here we present two powerful numerical modelling tools, which are relevant to each other and both can be used to investigate various biomimetic problems with their applications in ocean engineering. The first tool involves a combination of computational fluid dynamics (CFD) with a versatile multi-body dynamic (MBD) algorithm, which has been validated through several benchmark cases [3] and applied to examine the performance of a self-propelled pufferfish driven by fish multiple deformable fins.

A fluid-structure interaction (FSI) model is built in our second numerical tool, in which the flow is simulated by solving the Navier-Stokes equations with a finite-volume method based on the overset, multiblock grids, and the structural dynamics is resolved using nonlinear Euler-Bernoulli beams [4]. The FSI model is capable of simulating ray-supported fish fins with active and passive controls over the fin deformations. With this numerical model, the effects of various spanwise stiffness distributions on the propulsion performance of a three-dimensional ray-strengthened caudal fin are numerically investigated. The fin deformations are passively induced by the surrounding fluids and the results suggested that by appropriately cupping their fins, fish can achieve high efficiency. Considering that fish can both passively and actively control their fin shapes via changing the ray curvature and flexibility, we further studied the propulsion performance of an actively deformed caudal fin. It was revealed that, by undulation motion, fish are able to generate larger vertical force while producing little thrust. The findings may play important roles for bio-inspired robotic fins maneuvering behaviours, e.g., stabilizing and braking.

Currently, the fin kinematics adopted in our MBD model was reconstructed from an experimental measurement, which is subjected to a particular swimming status. To achieve a self-propulsion with multiple degree-of-freedoms motion, multiple fins have to cooperate so that the desired forces and motion trajectory could be optimally controlled. To achieve this goal, the insights shed from our FSI model study on the flow structure and force generation from fins are valuable to the design of the fin kinematics in our fish-body MBD tool. The optimization of fin kinematics and integration with control strategy, such as PID control, are our future work.

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