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NUMERICAL SIMULATION OF BATOID LOCOMOTION*

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Abstract: The hydrodynamics of batoid swimming motions is investigated using the three-dimensional simulation of a self-propelled body in still water. The kinematics of batoid swimming is characterized by large amplitude undulations of the pectoral fins while the middle part of the body remains straight. The majority of the thrust is generated by pectoral fins. Linear and quadratic amplitude variations are used for the pectoral fins in analyzing the locomotion of the batoid. Navier-Stokes equations are used to solve the unsteady fluid flow. A user defined function and a dynamic mesh method are applied to track the batoid locomotion. The mean swimming velocities of 1.6 BL/s and 1.3 BL/s are achieved, respectively, with thrust coefficients of 0.13 in and 0.095 in the dynamical simulation, where BL/s is the body length per second. The maximum propulsive efficiency 19% is achieved when the frequency of the undulation is 2.2 Hz in both amplitude variations.

Key words: batoid fish, undulation pectoral fin, dynamical simulation

Introduction

Batoids are unique among elasmobranch fishes in having dorsoventrally flattened bodies and pectoral fins that are greatly expanded and fused to the head, to form a broad, flat disc[1,2]. With the enlarged pectoral fins commonly found in batoids, there are multiple modes of locomotion. Among others, two widespread locomotion modes are the axial-based and pectoral-fin-based modes[3,4].

Pectoral-fin-based locomotion is traditionally divided into two forms: undulation and oscillation[5]. Undulation of pectoral fins, termed the "rajiform" locomotion, is one with more than one wave present on the fins at any time, while oscillation is one with less than half a wave[6,7]. In this article, we call undulation of pectoral fins with wave number greater than half a wave but less than one the rajiform locomotion. Rajiform swimmers propel themselves forward by propagating waves down their enlarged fins[8,9], which is responsible for a number of attractive features regarding this mode of locomotion, related both with kinematics and hydrodynamics. This article thus focuses on the undulation of pectoral fins of rajiform swimmers. In recent studies[10-15] the kinematic parameters of living batoids and bionic robotic batoids were analyzed, but studies of dynamical simulations of undulation batoids were very few.

In this article, the rajiform swimming is studied by using three-dimensional simulations of a self-propelled batoid-like body immersed in a viscous fluid. The simulation results provide quantitative information about three-dimensional fluid-body interactions, and can be used for quantitative analyses of the dynamics, which are difficult to obtain experimentally since we cannot let a living batoid to swim as we desire.

In addition, the simulation results are compared with the existing related studies, in order to assess the reliability of the three-dimensional simulation for the kinematics and hydrodynamics of rajiform swimming.

1. Material and methods

1.1 *Geometrical model*

Batoids are characterized by the streamlined flat body and the enlarged pectoral fins. The shape of the pectoral fins varies with the locomotion modes and wave numbers on them. In this study, we select Raja

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