Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **6**, No. 6, pp. 732-763

DOI: 10.4208/aamm.2013.m394
December 2014

Topology Optimization of the Caudal Fin of the Three-Dimensional Self-Propelled Swimming Fish

Zhiqiang Xin[1] and Chuijie Wu[1,2,*]

[1] *College of Mechanics and Materials, Hohai University, Nanjing 210098, China*
[2] *State Key Laboratory of Structural Analysis for Industrial Equipment & School of Aeronautics and Astronautics, Dalian University of Technology, Dalian 116024, China*

Received 3 November 2013; Accepted (in revised version) 30 April 2014

Available online 7 August 2014

Abstract. Based on the boundary vorticity-flux theory, topology optimization of the caudal fin of the three-dimensional self-propelled swimming fish is investigated by combining unsteady computational fluid dynamics with moving boundary and topology optimization algorithms in this study. The objective functional of topology optimization is the function of swimming efficiency, swimming speed and motion direction control. The optimal caudal fin, whose topology is different from that of the natural fish caudal fin, make the 3D bionic fish achieve higher swimming efficiency, faster swimming speed and better maneuverability. The boundary vorticity-flux on the body surface of the 3D fish before and after optimization reveals the mechanism of high performance swimming of the topology optimization bionic fish. The comparative analysis between the swimming performance of the 3D topology optimization bionic fish and the 3D lunate tail bionic fish is also carried out, and the wake structures of two types of bionic fish show the physical nature that the swimming performance of the 3D topology optimization bionic fish is significantly better than the 3D lunate tail bionic fish.

AMS subject classifications: 76Z10, 74F10

Key words: 3D bionic fish, caudal fin, topology optimization, swimming performance, vortex dynamics.

1 Introduction

Through hundreds of millions of years of natural evolution, most fishes achieve excellent swimming performance, which the motion performance of man-made vehicles can not catch up with. So the secret of fish swimming attracts interests and exploring of

*Corresponding author.
Email: cjwudut@dlut.edu.cn (C. J. Wu)

researchers from all areas. Gray estimated that the muscle energy of a dolphin at a swimming speed between 15 and 20 knots is one-seventh of the energy needed to drag a rigid body at the same speed [1]. The results of the study are known as the famous Gray's paradox, which promotes the study of fish swimming into a peak. From then on many researchers explain or challenge the conclusions of Gray's paradox. Lighthill studied anguilliform and carangiform swimming using the elongated-body theory. Wu proposed a two-dimensional waving plate theory for fish swimming [2]. However, these analytical methods can be only employed to calculate the thrust and the lateral forces of a undulating plates or a pitch-heave wing and have significant limitations in modeling realistic fish swimming. Cheng [3] developed a semi-numerical and semi-analytical method to analyze the propulsion mechanism of a 3D waving plate. Candelier et al. extended Lighthill's large-amplitude elongated-body theory of the fish locomotion to the three-dimensional movements, and founded that the results predicted with the three-dimensional extension theory are in good agreement with the data obtained in the numerical simulations [4].

Fish swimming is a unsteady flow process, and the swimming performance and features are closely related to wake structure generated in fish swimming. Fish can efficiently take advantage of the mechanism of unsteady flow. In order to reveal the efficient swimming mechanism of fish, it is necessary to analyze clearly the three-dimensional flow field around the swimming fish body using the advanced experimental techniques and numerical simulation methods. The experimental studies of fish swimming have made many important progress, for example, Lauder et al. [5,6] performed a large number of experiments of fish swimming, and systematically analyzed how different fishes use body and appendages to effectively implement flow control both actively and passively. Triantafyllou et al. [7,8] studied the relationship between the propulsive efficiency and the Strouhal number, and described the wake characteristics corresponding to the optimum propulsive efficiency. Due to the enormous difficulties in controlling fish swimming in the experiment, the numerical simulation is more effective in comparison with the experiment. The impact of various physical parameters and swimming patterns on the swimming mechanism, even evolutionary process and the geometry optimization of fish, can be carried out in the numerical simulation. Anderson and Wolfgang et al. shown the generation of the vortex around the fish body and the wake vorticity control during fish turning maneuver. Liu et al. [9] simulated tadpoles swimming by CFD, and analyzed the process of vortex shedding in the undulatory swimming. Wu and Wang [10]implemented numerical simulations of self-propelled swimming of the 3D bionic fish school based on the three-dimensional Navier-Stokes equations, and founded that fish control the swimming direction mainly by the swing of the head.

Fish are very diverse in the nature, and various types of fish have different shapes and swimming maneuvers. Generally, swimming locomotion can be divided into periodic swimming at a almost constant speed and transient movements, such as rapid maneuvers and turn etc. According to the swimming propulsors of fish, swimming modes are classified into the body and/or caudal fin swimming (BCF) and median and paired fin