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Hydrodynamic Analysis of Fish's Traveling Wave Based on Grid Deformation Technique

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In this paper, the hydrodynamic performance of a two-dimensional deformation plate is numerically simulated to mimic a fish's traveling wave by means of a grid deformation technique. The influence of main parameters, such as wavelength, linear wave amplitude, and wave frequency, on the hydrodynamic performance is analyzed. The total length of the plate selected is 0.3 m. The average thrust coefficients and propulsive efficiency, as well as the pressure contours varying with different parameters, are given to describe the results. The results show that, when the wavelength is 1.6–1.8 times the total length of the multi-joints, the thrust coefficient tends toward the maximum. The two main reasons for the change in thrust performance are (1) the pressure difference on both sides of the deformation plate and (2) the bending angle of the deformation plate, which affects the horizontal and vertical components.

INTRODUCTION

Because of its excellent maneuverability and low noise, the robotic fish plays an important role in sea farming, marine biological research, and marine ecological restoration. Different from a conventional propeller, the biomimetic propulsor provides a special propulsion mechanism for the design of micro underwater vehicles or bionic fish. The recent application of a biomimetic propulsor in underwater fish-like vehicles has made great progress. Romero et al. (2014) developed a cost-effective fish-like autonomous underwater vehicle (AUV) that could avoid obstacles in a swimming pool with a sophisticated intelligence. Lau et al. (2015) designed a bio-inspired wire-driven robotic fish, the Robot Shark, which can sway its caudal fin to establish forward motion as well as ascending motion. More about these investigations can be found in Raj and Thakur (2016) and Lamas and Rodriguez (2020).

To further investigate the propulsion mechanism, considerable research efforts have been devoted to the effects of deformation on the hydrodynamic performance of flapping plates in experimental methods. Heathcote and Gursul (2005) investigated a chordwise-flexible airfoil heaving with constant amplitude at different Reynolds numbers. The results revealed that stronger trailing-edge vortices corresponded to higher thrust coefficients, and weaker leading-edge vortices corresponded to higher efficiencies through measuring the flow field. Quinn et al. (2014) presented an experimental investigation of flexible panels actuated with heave oscillations at their leading edge, and the results showed that the propulsive economy increased with higher flexibilities that were mainly caused by the strong vortices attached to the leading edge. David et al. (2017) investigated the thrust production of a flapping foil, which consists of a rigid foil and a flexible flap, in a uniform flow, and revealed that the peak mean thrust coefficient was found to be 100% higher than the rigid foil thrust in an optimal reduced frequency, which could be explained by large values of vortex circulation and large lateral spacing of the vortices formed at the trailing edge of the flexible foil. All of these investigations promote our understanding of the application of biomimetic propulsion and clarify the problem in biomimetic propulsion.

In addition to the experimental explorations discussed above, much work has been done by numerical methods. Li et al. (2015) numerically simulated deformable flapping plates at low Reynolds numbers and analyzed the effects of trailing-edge flap deflection amplitude, deflection phase difference, and hinge location. The results revealed that the overall lift enhancement could reach up to 26% by selecting the optimal deflection amplitudes and deflection phase difference, which could be explained by the strengthened vortices at the leading edge of the foil. Hoover et al. (2018) studied a three-dimensional flexible panel that was heaved at its leading edge and mainly analyzed the influence of effective flexibility on propulsion performance. The results revealed that the main factor affecting the thrust force was alteration to the vortex structure near the trailing edge. For more representative studies, interested readers are referred to Wu, Liu, et al. (2015) and Wu, Wu, et al. (2015). Both the simulations and experiments show that the main factor affecting propulsion performance is the generation and evolution of vortices at the leading edge or trailing edge.

In recent studies (Liu and Hu, 2010; Yu et al., 2013), the mathematical model of the traveling wave proposed by Lighthill (1960) is widely used to model the fish-like swimming motion of multi-joint robotic fish. The origin is said to occur at the joining point between the fish body and tail.

$$y_{\text{body}}(x,t) = (c_1 x + c_2 x^2)\sin\left(\frac{2\pi}{\lambda}x - 2\pi f t\right) \tag{1}$$

Here, y_{body} is the lateral displacement of a tail unit from the center axis, x is the displacement along the tail, λ is the wavelength, c_1 is the linear wave amplitude envelope, and c_2 is the quadratic wave amplitude envelope. In this context, the value of c_2 is set to be 0. f is the wave frequency, and t is time.

Assuming that the main part of the bionic fish is rigid, Liu and Hu (2010) put forward the improved mathematical model by

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KEY WORDS: Hydrodynamic performance, robotic fish, traveling wave, grid deformation technique, Star-CCM+.