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Numerical study of rowing hydrofoil performance at low Reynolds numbers

M.-H. Chung*

Institute of Ocean Engineering and Technology, National Kaohsiung Marine University, Kaohsiung City 81143, Taiwan, ROC

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Abstract

In this paper, the hydrodynamic performance of a 2-D flat-plate hydrofoil in rowing motion is numerically studied by a Cartesian grid method with the cut-cell approach. Adaptive mesh refinement is used to save on the number of mesh cells without harming spatial resolution in critical regions. The rowing kinematics of the hydrofoil is the same for all simulations in this work. The design parameters studied are the reduced frequency of the rowing motion, the heave amplitude, and the time lags of the feathered-to-broadside rotation and the broadside-to-feathered rotation. Results show that larger thrust and efficiency can be attained if the feathered-to-broadside rotation is started right after the beginning of the power stroke and the broadside-to-feathered rotation is finished right before the end of the power stroke. Finally, both the thrust and the efficiency increase with Reynolds number.

Keywords: Rowing hydrofoil; Low Reynolds number; Cartesian grid method; Cut-cell approach; Adaptive mesh refinement

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1. Introduction

In the course of the development of aircraft and underwater vehicles, bird flight and fish swimming have been inspiring and guiding the engineers and scientists in the field of aerodynamics and hydrodynamics. Over the years, the science of biomimetics has been established and structured through the previous works of many researchers. For these man-made machines, the propulsion system plays a significant role which needs the knowledge and integration of hydrodynamics, structural mechanics, control theory, etc. For locomotion in water, propulsion by hydrofoil motion is very common. The types of motion can be put into two major categories. The first is the "flapping" motion, similar to the *thunniform* mode of fish swimming (Breder, 1926; Lindsey, 1978). The thunniform mode belongs to the body/caudal fin (BCF) propulsion and is by far the most efficient locomotion mode evolved in the aquatic environment, where thrust is generated with a lift-based method, allowing high cruising speeds to be maintained for long periods. Significant lateral movements occur only at the caudal fin (producing more than 90% of the thrust) and at the area near the narrow peduncle. Although the design of thunniform swimmers is optimized for high-speed swimming in calm waters, it is particularly inefficient for other actions such as slow swimming, turning maneuvers and rapid acceleration from stationary, as well as for turbulent water. The second is the "rowing" motion which is one of the chief ingredients in the *labriform* mode of fish swimming (Breder, 1926; Lindsey, 1978). The labriform mode belongs to the median/paired fin

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*Tel.: +886 7 3617141x3076; fax: +886 7 3602897.
E-mail addresses: mhsuan@mail.nkmu.edu.tw, meng.hsuan.chung@gmail.com

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(MPF) propulsion and is achieved by oscillatory movements of the pectoral fins. Blake (1983) identified two main oscillatory movement types for the pectoral fins: (i) a 'rowing' action (drag-based labriform mode) and (ii) a 'flapping' action (lift-based labriform mode). Drag-based methods are more relevant at slow speeds, while lift-based methods are more efficient at all flow speeds. Fins rarely perform a purely rowing or flapping movement; instead, a combination of the two, depending on the swimming speed, is used. It is estimated that about 15% of the fish families use non-BCF modes as their routine propulsive means, while a much greater number that typically rely on BCF modes for propulsion employ MPF modes for maneuvering and stabilization (Videler, 1993).

For real fish, the following swimming mode must be mentioned for completeness. That is, the BCF transient mode for fast starts or turns. Harper and Blake (1990) showed that fast-start acceleration of pike is significantly higher than that of trout for all performance parameters measured. They found that escape fast-start performance is related to body form. And their results support previous suggestions (Weihs, 1973; Lighthill, 1975; Webb, 1986) that the body form of pike is well-designed for BCF transient swimming and that of rainbow trout a compromise, showing some features that enhance BCF periodic (steady) swimming and some that benefit fast-start performance.

For the flapping motion, the following simple pitch-and-plunge (or heave) motion is most considered in the literature:

$$h = h_1 \sin(2\pi f_m t), \tag{1}$$

$$\alpha = \alpha_0 + \alpha_1 \sin(2\pi f_m t + \phi), \tag{2}$$

where h_1 is the plunge (or heave) amplitude, α_0 the mean pitch angle, α_1 the amplitude of the sinusoidal pitch angle variation, f_m the flapping frequency and ϕ the phase difference between the pitch-and-plunge motions. There has been a lot of experimental work to study and understand the basic mechanisms of force production and flow manipulation in oscillating (mostly flapping) foils for underwater use (Triantafyllou et al., 2004). The most comprehensive numerical investigations of the design parameter space are given by Isogai et al. (1999), Tuncer and Platzer (2000), and Ramamurti et al. (2001). All employed an NACA 0012 airfoil and solved the Reynolds averaged Navier–Stokes (RANS) equations. Isogai et al. (1999) and Tuncer and Platzer (2000) addressed compressible flows on a structured grid while Ramamurti et al. (2001) considered incompressible flows on an unstructured grid. The Reynolds number (Re) based on free-stream velocity and foil chord ranges from 10^3 to 10^5. All of them examined the effect of changing h_1, α_1, f, and ϕ on the average thrust coefficient and the thrust efficiency. Unfortunately, the results of Isogai et al. (1999) and Tuncer and Platzer (2000) differ by over 30% for some parameter combinations and the reason is not clear. Mittal (2004) argued that the turbulence modelling effects have to be examined. As for the results of Ramamurti et al. (2001), the computed thrust coefficient versus ϕ is generally consistent with the experiments of Anderson (1996) at $\mathrm{Re} = 1.1 \times 10^3$, but there is significant mismatch of thrust coefficient at higher frequencies with the experiments of Koochesfahani (1987) at $\mathrm{Re} = 1.2 \times 10^4$.

In contrast to the flapping motion, the rowing motion has received little attention in scientific research, neither in the numerical simulation nor in the experimental community. Though flapping motion is relevant for energy-efficient operation, such as is required during cruising, the rowing motion is more relevant to slow speed, maneuvering (starting, stopping, yawing, etc.) motion (Walker and Westneat, 2002). From a very crude pair of models of thrust-making device and assuming a constant drag and lift coefficient, Vogel (1996) calculated the average thrust, as a function of swimming speed, produced by the drag- and lift-based system, respectively. It was concluded that the drag-based system is very much better when the craft is nearly stationary but the lift-based system is clearly superior at higher swimming speeds. Recent blade-element computations (Walker and Westneat, 2000) also indicated that even though flapping motion is more efficient at all flow speeds, higher thrust can be generated at low speeds through a rowing motion. However, little is known about the wake topologies and other flow details for fins undergoing a rowing motion.

In this paper, a computational fluid dynamics research code based on the Cartesian cut-cell approach with adaptive mesh refinement was used to study the unsteady flow past a rowing hydrofoil at Reynolds numbers up to 1000. The simulations at higher Reynolds numbers are tentatively not conducted due to the above-mentioned unclear discrepancies found in the previous works. The viscous flow past a flat-plate hydrofoil at various rowing frequencies, heave amplitudes, and other design parameters, was simulated. Results are presented mainly in terms of the average thrust and the thrust efficiency versus the design parameters. The effect of Reynolds number is also investigated. The thickness ratio of the flat plate is $\frac{1}{20}$, with each end rounded by a semi-circle. As noted by Vogel (1996), the force coefficients of the lift-based system are much more sensitive to the cross-sectional shape of the plate than those of the drag-based system. Also shown in the work of Wang (2000) is that the force coefficients of elliptical cylinders with different thickness have almost the same functional dependence on the angle of attack but different magnitude. Thus a sufficiently thin flat plate would fulfill the purpose of the present work to find the tendency or functional relations with the design parameters.