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Propulsive performance of a flapping plate near a free surface

Meng-Hsuan Chung

Department of Naval Architecture and Ocean Engineering, National Kaohsiung Marine University, No. 142, Haijhuan Rd., Nanzih District, Kaohsiung City 811, Taiwan, ROC

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ABSTRACT

The propulsive performance, i.e., the time-averaged thrust coefficient or the propulsive efficiency, of a flapping flat plate advancing near an otherwise quiescent free surface (liquid–gas interface) with *Re* of 1000, *Fr* of 0.2 and 0.8, and various submergence depths is numerically investigated by employing an adaptive Cartesian cut-cell/level-set method. The flapping kinematics parameters excluding the pitch-leading-heave phase angle were fixed as those commonly seen in literature. Results show that for submergence depth larger than the heave amplitude, the propulsive performance peaks at a smaller pitch-leading-heave phase angle with a shallower submergence for *Fr* of 0.2 but at the same phase angle for *Fr* of 0.8. Proximity to the free surface enhances the peak propulsive performance for *Fr* of 0.2 but the influence is minor for *Fr* of 0.8. The propulsive performance with *Fr* of 0.2 increases with decreasing chord-normalized submergence depth for the pitch-leading-heave phase angle smaller than 100°. The trend is reversed for the pitch-leading-heave phase angle larger than 100°. However, the propulsive performance with *Fr* of 0.8 hardly depends on the chord-normalized submergence depth. For submergence depth equal to the heave amplitude, the temporal variation in the thrust coefficient exhibits characteristics inherently different from those with other submergence depths for *Fr* of 0.2. Also, the time-averaged thrust coefficient exhibits a unique variation with the pitch-leading-heave phase angle. However, the various characteristics of the propulsive performance are similar to those with other submergence depths for *Fr* of 0.8. For submergence depth smaller than the heave amplitude and *Fr* of 0.2, the propulsive performance gains much from exposure of the upper surface of the plate to the gas phase. The efficiency enhancement is linked to the weakening of the leading edge vortices. A second harmonic with significant amplitude is found in the upstream wave for *Fr* of 0.2 with a typical pitch-leading-heave phase angle.

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1. Introduction

In designing and studying man-made vehicles, locomotion (flight or swimming) of natural species is a good source of inspiration and rule of guidance for the engineers and scientists in the field of aerodynamics or hydrodynamics. For these vehicles based on the science of biomimetics, the propulsion system plays a significant role. For locomotion in water, propulsion by flapping hydrofoil is very common. It is similar to the *thunniform* mode of fish swimming (Breder, 1926; Lindsey, 1978) which is by far the most efficient locomotion mode in nature evolving in the aquatic environment, capable of maintaining high cruising speeds for long periods. For this mode of locomotion, the swimmer's body keeps nearly straight

E-mail addresses: mhsuan@webmail.nkmu.edu.tw, meng.hsuan.chung@gmail.com

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and significant lateral movements occur only at the caudal fin (producing more than 90% of the thrust) and at the area near the narrow peduncle. On the other hand, the flapping motion, combining with the rowing motion (Blake, 1983), can well model the oscillatory movements of the pectoral fins in the *labriform* mode of fish swimming (Breder, 1926; Lindsey, 1978) which is suitable for maneuvering and stabilization (Videler, 1993).

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

$$y_h(t) = h_1 \sin(2\pi f t), \tag{1}$$

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

where $y_h(t)$ and $\alpha(t)$ are the instantaneous heave position of the pitch axis and angle of attack respectively, h_1 the heave (or plunge) amplitude, α_0 the mean pitch angle, α_1 the amplitude of the sinusoidal pitch angle variation, f the flapping frequency and δ the phase angle of pitch leading heave. The Reynolds number, *Re*, is defined as Uc/ν where U represents the free stream velocity, c the foil chord, and ν the kinematic viscosity of the fluid. There has been a lot of experimental works on underwater oscillating (mostly flapping) foils (Triantafyllou et al., 2004). The most comprehensive numerical investigations were given by Ramamurti and Sandberg (2001), who solved the Reynolds Averaged Navier-Stokes (RANS) equations using a finite element method on an unstructured grid for the NACA 0012 foil. The predicted thrust coefficient versus δ is generally consistent with the experiments of Anderson (1996) at *Re* of 1.1×10^3, but there is significant disagreement of higher-frequency thrust coefficients with the experimental results of Koochesfahani (1987) at *Re* of 1.2×10^4. For inviscid flows the thrust and power coefficients reach their minima and the propulsive efficiency its maxima approximately at δ of 90° for a low-frequency and small-amplitude flapping foil , as indicated in the review paper by Platzer et al. (2008). For viscous flows in the above regimes of Reynolds number, the maximum efficiency also occurs at δ of about 90° and the leading edge vortex (LEV) is beneficial to the thrust enhancement but harmful to the propulsive efficiency (Platzer et al., 2008). In contrast to the inviscid flow, the maximal thrust coefficient and the peak efficiency occur at approximately the same phase angle (Ramamurti and Sandberg, 2001). It is interesting to investigate the effects of free surface proximity on the pitch-leading-heave phase angle with the peak performance and the relation between the propulsive efficiency and the LEV.

Hydrodynamics of foil oscillating beneath a free surface has attracted less attention as compared to that in unbounded fluid. Two additional parameters, i.e., Froude number *Fr* ($\equiv U/(gc)^{1/2}$ with g denoting the gravitational acceleration) and depth of submergence, have to be considered in this problem setup. Isshiki (1982a) improved the linearized potential flow theory for oscillating foil propulsors in waves (Wu, 1972; Wu and Chwang, 1975) by including the free surface effect and applied it to the investigation of a passive-type hydrofoil propulsor (Isshiki, 1982b; Isshiki and Murakami, 1984). Isshiki (1982b) pointed out a possibility of an optimum depth of submergence for the wave devouring efficiency when the foil moves without oscillation. Similarly, Grue et al. (1988) studied a flapping flat plate moving with a prescribed forward speed in calm water or waves. They found that, for moderate values of Uf/g, the free surface strongly influences the vortex wake and the forces upon the foil. However, at some lower wave numbers there were significant discrepancies between their theory and experimental results of Isshiki and Murakami (1984). They attributed these inconsistencies to not considering non-linear effects and modeling only partial free-surface effects in the theory. Zhu et al. (2006) and Cleaver et al. (2013) studied a plunging foil beneath a free surface, using the potential flow theory and experimental test respectively. Cleaver et al. (2013) found that the drag reduction as a function of the dimensionless plunging frequency departures more from the predictions by the inviscid linear theory (Garrick, 1937) with decreasing submergence depth. Vortex lock-in was reported for the first time in experiments. Xu and Wu (2013), via the linearized potential flow theory, analyzed wave radiation and diffraction of a surge-heave-pitch hydrofoil advancing in waves. The effects of submergence depth were not discussed, only knowing that it was set to some values larger than 0.6*c*. Further, propulsive performance was not of their concern. Filippas and Belibassakis (2014), based on the boundary-element-method numerical results for two depths of submergence (1.5*c* and 2.5*c*), concluded that the thrust coefficient is more reduced when a flapping foil advances closer to a calm free surface, essentially due to development of wave resistance.

Although some effects of the submergence depth and Froude number have been investigated in the above literature, the former was always limited to large values for not touching/piercing the free surface. Further, all the theoretical analyses were based on the potential-flow assumption, causing difficulty or even impossibility to resolve complicated viscous flows, e.g., those due to large-amplitude motion of foil. In recent years, De Silva and Yamaguchi (2012) used the commercial software FLUENT to numerically study the potential of wave energy exploitation by an active-type flapping-foil propulsor with *Re* of 5×10^7. There were only few choices of submergence depth ($> 1c$) and no systematic analysis was conducted. To gain deep insight into the fluid dynamics mechanism associated with a flapping foil advancing in waves, the study on a flapping foil advancing near an otherwise quiescent free surface should be first conducted. In a similar respect, Kajtar and Monaghan (2012) applied the Smoothed Particle Hydrodynamics (SPH) method to study the two-dimensional fish-swimming (mimicked by three linked relative-angle-changing rigid bodies) performance near a free surface. The energy consumption per unit distance is lowest when the fish swims within one third of the fish length from the free surface if wave breaking is not severe, as compared with deeper swimming. This trend is inconsistent with that of the thrust coefficient in inviscid flows mentioned above (Filippas and Belibassakis, 2014). Finally, the influences of Froude number were not discussed.

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