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# Propulsion of an active flapping foil in heading waves of deep water

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ABSTRACT

The propulsion of a flapping foil in heading waves has been investigated through the velocity potential theory. The trajectory of the flapping foil is prescribed with the combined sinusoidal heave and pitch motions. Boundary element method is introduced to solve the boundary value problem and a time stepping scheme is adopted to simulate the interaction of the foil and Stokes waves of infinite water-depth. The nonlinear free surface boundary conditions are imposed when updating the free surface. The effects of the frequency difference between foil motion and waves have been investigated. When the encountered wave frequency equals the flapping frequency, hydrodynamic performance of the flapping foil can be enhanced significantly.


## 1. Introduction

Propulsion through bio-inspired flapping foil can be highly efficient. Active flapping foils are applicable for the propulsion of ships or underwater vehicles. When foils are mounted on the bow of a ship, they will move with the ship in waves. The foils can improve the sea keeping performance of the ship and would assist the propulsion [1–3]. The foil is known as wavefoil. The progress of the wavefoil for propulsion had been reviewed by Rozhdestvensky and Ryzhov [4] and Belibassakis and Politis [5]. The hydrodynamics of the wavefoil is affected by the free surface, the incident wave and motion of the ship. The propulsive performance of these foils, either passive or active, shall consider the cross effects of these factors. Ignoring the disturbance of the ship, a two dimensional foil oscillating in wave will be studied in present study.

Flapping foil for propulsion originates from the locomotion of animals. Considering the flexibility of realistic wings or fins, the mechanism of the propulsion can be very complex. Early work by Lighthill [6] and Wu [7,8] reduced the problem to a waving plate and the propulsion force was calculated indirectly through complex theory. After that, studies mainly concerned rigid oscillatory foil with harmonic heave and pitch motions [9–12]. Ashraf et al. [13] and Xiao and Liao [14] investigated the propulsion of a flapping foil through solving Navier–Stokes equation. The optimum motion parameters for higher efficiency were investigated. As analysed in Anderson et al. [10] and Xu and Wu [12], the propulsive rigid foil in harmonic motion is dominated by the Strouhal number *St*, effective attack angle $\alpha_0$, heaving amplitude $h_0$ and the phase difference $\varepsilon$. Read et al. [15] further revealed that the modified non-sinusoidal heave motion, which actually increased the mean effective attack angle in upstroke and downstroke motion at high frequency, increased the propulsive efficiency significantly.

The free surface flow has significant effects on the hydrodynamics of a foil as the submergence is shallow. For a foil travelling at constant speed with fixed attack angle, its lifting force would increase or decrease significantly when various submergences and Froude number are considered [16–20]. The induced surface wave flow would change the local flow around the foil and therefore the effective attack angle. Zhu et al. [21] investigated the effects of initial quiescent free surface on the propulsion of an oscillating foil through boundary element method. The thrust and the propulsive efficiency decrease when moderate motion amplitudes are considered.

The oscillating surface wave flow will affect the propulsive performance of the foil. Wu [22] included the effect of the incoming wave, but the free surface boundary condition was not satisfied when solving the boundary value problem (BVP). Grue et al. [23] studied the propulsion of an oscillating plate in waves through linear theory in frequency domain; it was reported that the wave energy could be utilized to promote the propulsive efficiency. Filippas and Belibassakis [24] had simulated the propulsion of flapping foil in linear surface waves; they found that the thrust can maximally increase 20% if proper motion parameters were adopted. In previous studies, the considered wave-foil interactions were in regular waves. Belibassakis and Filippas [2] further investigated the coupled motion of a ship hull with semi-active foil in random waves. The vertical motion of the foil was dominated by the heave and pitch motions of the ship and the rotational motion was actively controlled; the ship-foil system produced significant thrust and augmented the ship propulsion. If an active foil is utilized for the propulsion of ships or surface vehicles, the frequency of the flapping foil is not necessarily equal

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to the encountered wave frequency. As suggested by Anderson et al. [10] and Trantafyllou et al. [25], the efficiency of the propulsive foil depends on the Strouhal number and secondarily the heave and pitch amplitudes. To achieve higher propulsive efficiency, the frequency of an active flapping foil would differ the encountered wave frequency. The hydrodynamics of the flapping foil in waves of various wave frequencies seems to have been ignored. The effects of surface wave flow will cause the variation of the instantaneous effective attack angle. The performance of flapping foil requires insightful investigations.

The performance of an active foil in nonlinear waves will be investigated in present study. The trajectory of the flapping foil is prescribed through harmonic heave and pitch motions. Small to medium effective attack angle is considered. Therefore only trailing edge vortex shedding is included. The fifth order Stokes wave of infinite water-depth is adopted as the nonlinear incident wave. The interaction of the incident wave and the flapping foil is simulated through time stepping scheme. In Section 2, the motion of the foil, the boundary value problem and the incident waves will be described. In Section 3, the small amplitude motion is considered after the numerical code is validated; propulsion of larger amplitude oscillatory motion in waves is further investigated. The effects of the wave number and flapping frequency are analysed.

## 2. Formulations

### 2.1. Motions of the foil

A flapping foil advancing at constant horizontal speed $U$ is considered. The submergence, which is measured from the rotational centre to the initial quiescent surface, is denoted as $H$. The trajectory of the flapping foil is prescribed through the sinusoidal heave and pitch motions, we have

$$h(t) = h_0 \sin \omega t \tag{1}$$

$$\theta(t) = \theta_0 \sin(\omega t + \varepsilon) \tag{2}$$

where $h_0$ and $\theta_0$ are the heave and pitch amplitudes respectively; $\omega$and $\varepsilon$ are the circular frequency and phase difference; the positive direction of pitch angle $\theta(t)$ is defined as counter clockwise; the rotation centre is located at one third of the chord referring to the leading edge.

The harmonic motion of a foil is determined by the Strouhal number $St = \frac{\omega h_0}{\pi U}$, heave amplitude $h_0$, pitch amplitude $\theta_0$ or the nominal amplitude of effective attack angle $\alpha_0$ and the phase difference $\varepsilon$. The phase difference $\varepsilon = 90^\circ$ is adopted. We have the effective attack angle and its nominal amplitude at the pivot centre

$$\alpha(t) = \arctan \frac{\dot{h}(t)}{U(t)} - \theta(t) \tag{3}$$

$$\alpha_0 = \arctan \frac{\omega h_0}{U} - \theta_0 \tag{4}$$

In the propulsive motion mode, the attack angle is positive during upstroke motion and negative during downstroke motion. The average attack angle is zero. The maximum effective attack angle appears when the foil is at its mean position.

### 2.2. Governing equation and boundary conditions

As shown in Fig. 1, a foil travelling beneath water waves is considered. Its chord length is denoted as $C$. Two right-handed Cartesian coordinate systems are defined. One is the space-fixed coordinate system $O_0x_0z_0$ with the plane on the initial quiescent water surface and $z_0$-axis being positive upwards. The other is a translational coordinate system $oxz$, which is moving along with the foil at constant horizontal speed $U$. At the initial time, these two sets of coordinate systems are coincident. The relationships between these two coordinate systems are

$$x_0 = x + Ut, \quad z_0 = z \tag{5}$$

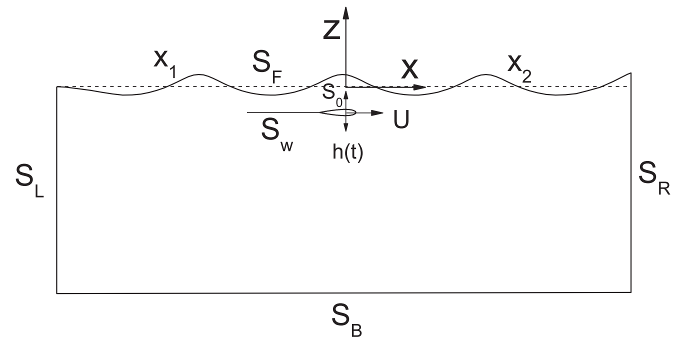


**Fig. 1.** The sketch of a flapping foil in waves.

The velocity potential $\phi(x, z, t)$ is introduced; it represents the total velocity potential due to wave body interactions. The velocity potential observed in the space-fixed coordinate system can be also described in the translational coordinate system, that is

$$\phi_0(x_0, z_0, t) = \phi(x, z, t) = \phi(x_0 - Ut, z_0, t) \tag{6}$$

The foil travelling at constant horizontal speed $U$ is equivalent to the current flowing at constant horizontal speed $U$ in the opposite direction. The relative velocity potential observed in the translational coordinate system is introduced

$$\phi_r(x, z, t) = \phi(x, z, t) - Ux \tag{7}$$

where $-Ux$ denotes the contribution of the equivalent current.

The velocity potential $\phi_0(x_0,z_0,t)$ satisfies the Laplace equation in the whole field in the space-fixed coordinate system, we have

$$\frac{\partial^2 \phi_0}{\partial x_0^2} + \frac{\partial^2 \phi_0}{\partial z_0^2} = 0 \tag{8}$$

We have dynamic and kinematic free surface boundary conditions on the instantaneous free surface $S_F$

$$\frac{\partial \phi_0}{\partial t} = -\frac{1}{2}\left[\left(\frac{\partial \phi_0}{\partial x_0}\right)^2 + \left(\frac{\partial \phi_0}{\partial z_0}\right)^2\right] - g\eta_0 \tag{9}$$

$$\frac{\partial \eta_0}{\partial t} = \frac{\partial \phi_0}{\partial z_0} - \frac{\partial \phi_0}{\partial x_0}\frac{\partial \eta_0}{\partial x_0} \tag{10}$$

where $g$ represents the acceleration due to gravity, $\eta_0$ is the wave elevation on free surface.

The body surface boundary condition is satisfied on the exact moving foil surface $S_0$, we have

$$\frac{\partial \phi_0}{\partial n_0} = \mathbf{V}_0 \cdot \mathbf{n}_0 = (U - \dot{\theta}Z)n_x + (\dot{h} + \dot{\theta}X)n_z \tag{11}$$

where $\vec{X} = (X, Z) = (x - x_c, z - z_c)$, $(x_c, z_c)$ is the centre of rotational motion, and $\vec{n} = (n_x, n_z)$ is the inward normal vector of the body surface.

In the far field, the disturbed wave will propagate to infinity and there should be no reflection. Numerically, the disturbed wave will be absorbed using damping zone technique and then diminishes on the truncated boundary. On the left side surface $S_L$ and the right side surface $S_R$ we have

$$\frac{\partial \phi_0}{\partial n_0} = \frac{\partial \phi_I}{\partial n_0} \tag{12}$$

where $\phi_I$ is the potential of the incident wave which will be described in Section 2.3.

The concerned problem is aiming for deep water. The integral boundary on the bottom $S_B$ is included for the completeness of the integral boundary over the fluid domain. It will not affect the numerical results as long as the depth is large enough. The boundary condition on $S_B$ satisfies

$$\frac{\partial \phi_0}{\partial n_0} = 0 \tag{13}$$