Design of flapping-foil thrusters for augmenting ship propulsion in waves

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ABSTRACT: Flapping wings located beneath or sideways the hull of the ship, operating in waves, while travelling at constant forward speed, are investigated as unsteady thrusters, augmenting the overall ship propulsion in waves. The main arrangement consists of horizontal wing(s) in vertical oscillatory motion which is induced by ship heave and pitch, while pitching about the wing pivot axis is actively controlled. In previous works, potential based panel methods have been developed for the hydrodynamic analysis of the system, including the effects of the free surface, which are found to be in agreement with numerical predictions from other methods and experimental data. Also, it has been demonstrated that significant energy can be extracted by the present system from waves. In this work we further examine the possibility of energy extraction by the system in irregular wave conditions using active pitch control. More specifically, we consider operation of the flapping foil in waves characterized by a spectrum, corresponding to specific sea states, taking into account the coupling between the hull and the flapping foil dynamics. The present method takes into account the effect of the wavy free surface through the satisfaction of the corresponding boundary conditions, as well as the velocity component due to waves on the formation of the incident flow. Numerical results concerning thrust coefficient are presented, indicating that significant efficiency can be obtained under general operating conditions. The present work can be exploited to derive guidelines concerning the design and optimum control of such systems extracting energy from sea waves for augmenting marine propulsion in rough seas, with simultaneous reduction of ship responses offering dynamic stabilization.

1 INTRODUCTION

Greening of sea transport has been recognized to be an important factor concerning energy saving and protection against global warming and climatic change effects. This is especially true, since contribution of cargo ships to world pollution has been recognised as a significant factor, taking also into account the bad fuel quality of seagoing vessels in relation to other modes of transport. In this direction, the optimization of propulsive efficiency of ships operating in realistic sea states is considered very crucial; see for example the study Belibassakis et al (2013) where the effects of added resistance and propeller-wave interaction are considered. On the other hand, evolution of air and sea creatures, through million years of natural selection/optimization, arrived to the flapping wing as their single propulsion system. Also, research and development concerning flapping foils and wings, supported by extensive experimental evidence and theoretical analysis, has shown that such systems at optimum conditions could achieve high thrust levels; see, e.g., Triantafyllou et al (2000,2004), Taylor et al (2010), von Ellenrieder et al (2008).

In real sea conditions, the ship undergoes moderate or higher-amplitude oscillatory motions, due to waves, and the vertical ship motion could be exploited for providing one of the modes of combined/complex oscillatory motion of a biomimetic propulsion system free of cost. The initial attempts in this direction were focused on the application of passively flapping wings underneath the ship hull, to transform energy stored in ship's motions to useful propulsive thrust, with simultaneous reduction of unwanted responses; see, for example, Rozhdestvensky & Ryzhov (2003) for an extensive review, Naito & Isshiki (2005) for a review in flapping-bow wings on ship propulsion, Bøckmann & Steen (2013) and Terao & Sakagami (2013) for experimental research and full-scale applications, respectively.

Working in the above direction Belibassakis & Politis (2013) proceed by substituting the passive pitching setup by an active pitching control, using a proper control mechanism and a pitch setup algorithm, on the basis of the (known) random motion history of the wing, and developing theoretical and
Figure 1. Ship hull equipped with a flapping wing located below the keel, at a forward station.

numerical tools capable of analyzing/designing ships equipped with such biomimetic wing propulsors, producing thrust by extracting energy from waves, as illustrated in Fig.1. The wing undergoes a combined transverse and rotational oscillatory motion, while the ship is steadily advanced in the presence of waves, modeled by directional spectrum. The vertical motion of the wing is induced by the random motion of the ship in waves, essentially due to ship heave and pitch, at the station where the flapping wing is located. Wing pitching motion is controlled as a proper function of wing vertical motion and it is imposed by an external mechanism. Calculations are based on coupling the seakeeping operators associated with the longitudinal and transverse ship's motions with the hydrodynamic forces and moments produced by the flapping lifting surfaces, using unsteady lifting line theory and nonlinear 3D panel methods (Politis 2011) in infinite domain. First numerical results presented in Belibassakis & Politis (2013) indicate that significant levels of thrust and antirolling moment are produced in sea conditions of moderate and higher severity, under optimal control settings.

Similar two-dimensional problem concerning wave energy extracting systems has been studied by Ishihiki (1982). For the detailed investigation of the effects of the free surface on the oscillating body hydrodynamics, in Filippas & Belibassakis (2014), a potential-based boundary element method has been developed and applied to the hydrodynamic analysis of a 2D hydrofoil operating beneath the free surface, undergoing flapping motion in monochromatic waves. Numerical results are presented concerning various hydrodynamic quantities over a range of parameters compared against other results from the literature and calculations in infinite domain. The results are found to be in good agreement with numerical predictions from other methods and experimental data. Also, it has been demonstrated that the free-surface effects are important and cannot be neglected. We have also seen that, under the appropriate conditions, significant thrust can be produced in the presence of incoming harmonic waves.

In the present paper we apply the developed BEM (Filippas & Belibassakis 2014) to examine further the possibility of energy extraction under more realistic, multichromatic wave conditions, using active pitch control, taking into account the coupling between the hull and the flapping foil dynamics. More specifically, we consider operation of the foil in head waves characterized by a given frequency spectrum, corresponding to specific sea states. The heaving motion of the foil is calculated using the energy spectrum of the incident wave field and the response amplitude operator (RAO) of the ship at the location of the foil. RAO calculations are based on coupling the seakeeping operators associated with the longitudinal and transverse ship's motions with the hydrodynamic forces and moments produced by the flapping lifting surfaces, using unsteady lifting line theory; Belibassakis & Politis (2013). The developed potential method takes into account the effects of the wavy free surface through the satisfaction of the corresponding boundary conditions. Numerical results concerning thrust coefficient are presented, indicating that significant efficiency can be obtained under optimal operating conditions.

The present work is structured as follows: In Sec. 2 the developed seakeeping model for the calculation of the complex system responses with the operation of the flapping thruster is presented. Subsequently, in Sec.3 the modeling of random multichromatic waves and the kinematics of the foil motion based on the calculated RAO is discussed. Also, the computational method applied to treat the flapping foil hydrodynamics, in detail, is presented. Finally, in Sec.4 the behavior of the above system is examined in random waves, represented by various frequency spectra, and numerical results are provided and discussed.

2 SHIP DYNAMICS

For demonstration purposes, we consider a series 60 - $C_b$=0.60 ship hull form, with main dimensions length $L$=50m, breadth $B$=6.70m that floats at a draft $T$=2.80m. The exact value of the block coefficient at the above draft is $C_b$=0.533. From hydrostatic analysis, the immersed volume in the mean position is $V_{w}$=500m$^3$, and the corresponding displacement in salt water, which equals the mass of the ship, is estimated $\Delta$=512tn. Moreover, in the above draft, the wetted area of the hull is calculated $S_{wet}$=380m$^2$, the waterplane area $A_{WL}$=225m$^2$, the center of flotation $x_f$ = -1.15m (LCF aft midship), the longitudinal moment of inertia of the waterplane is $I_{L}$=28800m$^4$, and the corresponding metacentric radius $BM_L$=57.6m. The vertical center of buoyancy is $KB$=1.55m (from BL), and the longitudinal position is $LCB$=0.266m.
For simplicity, we consider the long-center of gravity to coincide with the center of buoyancy, i.e., \( X_G = -0.266 \text{m} \) (aft midship), \( Y_G = 0 \), and \( KG = 1.80 \text{m} \) (from BL), and thus, the metacentric height in the above condition are estimated to be \( GM = 0.9 \text{m} \). Also, the longitudinal metacentric height in the above condition is approximated by \( GM_T \approx BM_T \). Finally, the radii of gyration about the x-axis and y-axis, respectively, are taken \( R_{xx} = 0.32L \), \( R_{yy} = 0.23L \).

The flapping wing propulsor is located at a distance \( x_{wing} = 15 \text{m} \) fore the midship section (station 8 of the ship), at a depth \( d = 7 \text{m} \) below WL. The half-wing planform shape is trapezoidal and its span is \( s = 6 \text{m} \). Moreover, the root and tip chords of the wing have lengths \( c_r = 1 \text{m} \), \( c_t = 0.5 \text{m} \), respectively, and the leading edge sweep angle is \( A_s = 9.4 \text{deg} \). On the basis of the above, the wing planform area is \( S_w = 4.5 \text{m}^2 \), and its aspect ratio \( AR = 8 \). The wing sections are symmetrical NACA0012. The same ship and wing geometry has been examined in Belibassakis & Politis (2013) showing very satisfying performance.

### 2.1 Equations of motion

Standard linearized seakeeping analysis in the frequency domain (see also Belibassakis & Politis 2013) is used to obtain the motions and responses of the examined system (ship and flapping wing). The coupled equation of heave and pitch motion of the ship (with corresponding complex amplitudes \( \xi_{30} \) and \( \xi_{50} \)) is as follows (taking the origin at the center of gravity):

\[
D_{33} \xi_{30} + D_{35} \xi_{50} = F_{30} + X_{30}, \tag{2.1a}
\]

\[
D_{53} \xi_{30} + D_{55} \xi_{50} = F_{50} + X_{50}, \tag{2.1b}
\]

where

\[
D_{33} = \left( -\omega^2 \left( m + a_{33} \right) + i \omega b_{33} + c_{33} \right), \tag{2.2a}
\]

\[
D_{35} = \left( -\omega^2 \left( a_{35} + i \omega \right) + i \omega b_{35} + c_{35} + p \right), \tag{2.2b}
\]

\[
D_{53} = \left( -\omega^2 \left( a_{35} + i \omega \right) + i \omega b_{33} + c_{35} \right), \tag{2.2c}
\]

\[
D_{55} = \left( -\omega^2 \left( a_{55} + i \omega \right) + i \omega b_{53} + c_{55} \right), \tag{2.2d}
\]

\( a_{jk} \) and \( b_{jk}, j, k = 3, 5 \), are added mass and damping coefficients, \( m \) is the total mass of the ship and wing and \( p = -i \omega \rho U m \). The involved hydrostatic coefficients are \( c_{33} = \rho g A_{WL}, c_{35} = c_{53} = -\rho g \left( x_{A_{WL}} \right) \) and \( c_{55} = m g GM_L \). The inertia coefficients involved in the above system are \( I_{55} = mR_{yy}^2 \) and \( I_{35} = I_{53} = -mX_G \). For simplicity only head waves (\( \beta = 180^\circ \)) are considered here as excitation of the hull oscillatory motion and the frequency of encounter (relative frequency) is

\[
\omega_m = \omega + kU = \omega + \omega^2 U / g. \tag{2.3}
\]

where \( k = \omega^2 / g \) is the wavenumber of the incident waves related, through deep water dispersion relation, with the absolute (angular) frequency \( \omega \).

The terms \( F_{j0}, j = 3, 5 \) appearing in the right-hand side of Eqs.(2.1) and (2.2) are the Froude-Krylov and diffraction vertical force and pitching moment (about the ship y-axis) amplitudes, respectively. Furthermore, the terms \( X_{j0}, j = 3, 5 \) denote additional force and moment amplitudes due to the operation of the horizontal flapping wing as an unsteady thruster. The latter are dependent on heave \( (\xi_h) \) and pitch \( (\xi_p) \) responses of the ship, as well as to the incoming wave field. In the present work we exploit the approach developed in Belibassakis and Politis (2013) and we use a simplified lifting-line model to derive expressions of the flapping wing forces \( X(\xi) \) in Eqs.(2.1) and (2.2) in terms of the oscillatory ship amplitudes and include in this way the effects of flapping wing in the system coefficients. These forces are separated into two parts: \( X(\xi) = X_A(\xi) + X_B(\phi_{INC}) \), one part dependent on the oscillatory ship amplitudes and one dependent on the incoming wave potential \( \phi_{INC} \). The first part produces modifications of the hydrodynamic coefficients of the system and the other part adds on the Froude-Krylov and diffraction forces in the right-hand side (see also Sclavounos & Borgen 2004).

In the examined case the working angle of attack of the flapping wing is given by:

\[
a(t) = -\xi_h(t) + \varepsilon(t) + \frac{\partial \phi_{INC}}{U \partial z} - \delta(t), \tag{2.4}
\]

where \( \delta(t) \) denotes the flapping wing pitch angle (the controlled variable). The above formula is obtained by linearizing the tangent for small angles. The second term in the right-hand side is due to the contribution of oscillatory motion(s) of the ship and this part, considered all together, is denoted by

\[
\varepsilon(t) = \frac{1}{U} h(t), \tag{2.5}
\]

where \( h(t) = -\frac{d \xi_h(t)}{dt} + x_{wing} \frac{d \xi_h(t)}{dt} \) denotes the vertical motion of the foil due to the oscillation of
the system and $x_{wing}$ denote its position along the ship. As it has been suggested by Politis & Politis (2012) and Belibassakis & Politis (2013), the controlled pitch angle is set proportional to the oscillatory angle $\delta(t) = w \varepsilon(t)$, with the pitch control parameter $w$ ranging from 0 to 1, and thus, the angle of attack finally becomes

$$a(t) = -\xi(t) + (1 - w) \varepsilon(t). \quad (2.6)$$

Unsteady lifting line models based on the integration of 2D sectional lift along the span can be used to obtain the wing lift and moment (about the pivot axis at distance $x_k$ from the leading edge) coefficients. In the case of flapping wings operating at relatively low reduced frequencies of oscillation, the spanwise integration could be simplified (see Belibassakis & Politis 2013), leading finally to following approximate expressions

$$X_{30} = \frac{1}{2} \rho U^2 S_w C_{L}^{3D} \approx \frac{1}{2} \rho U^2 S_w \frac{AR}{AR + 2} C_{L}^{3D} = G\alpha_0 + \frac{Gc_R h_b}{4U^2} \omega^2, \quad (2.7)$$

$$X_{30} = \frac{1}{2} \rho U^2 S_w C_{M} - \frac{1}{2} \rho U^2 S_w C_{L}^{3D} x_{wing} \approx -x_{wing} X_{30}, \quad (2.8)$$

where $G = \chi \pi \rho U^2 S_w \frac{AR}{AR + 2}$ with $\chi$ an appropriate correction factor (see Belibassakis & Politis 2013). Using the above in Eqs. (2.1) and (2.2), we obtain the following modifications of the system (hull and flapping wing) damping and restoring-force coefficients due to the operation of the horizontal flapping wing (from the term $X_\delta (\xi) )$:

$$\delta a_{33} = G (1 - w) / U, \quad (2.9a)$$

$$\delta b_{33} = -G (1 - w) x_{wing} / U, \quad (2.9b)$$

$$\delta b_{35} = -G (1 - w) x_{wing} / U, \quad (2.9c)$$

$$\delta c_{35} = G, \quad (2.9d)$$

$$\delta c_{55} = -G x_{wing} . \quad (2.9e)$$

Also, the flapping wing added mass leads to corresponding changes in the system coefficients as

$$\delta a_{33} = -G c_R / (4U^2), \quad (2.10a)$$

$$\delta a_{35} = \delta a_{53} = x_{wing} G c_R / (4U^2), \quad (2.10b)$$

Finally, the following expressions are derived concerning the part $X_\delta (\theta Rc)$ of the hydrodynamic vertical force and moment due to the flapping wing which is not dependent on the ship-motion amplitudes:

$$X_{30} = G (1 - w) (i \omega / U) \exp(-kd + ikx), \quad (2.11)$$

$$X_{30} = -G (1 - w) x_{wing} (i \omega / U) \exp(-kd + ikx), \quad (2.12)$$

where $z = -d$ denotes the mean position below the free surface of the flapping wing (mean submergence of the flapping wing). The linearized thrust coefficient is estimated from the corresponding lift coefficient as follows

$$C_T = \frac{T}{0.5 \rho U^2 S_w} = C_{L}^{3D} \sin(\theta_s), \quad (2.13)$$

where $\theta_s = \theta + \alpha$ if the sectional lift is assumed normal to the instantaneous inflow, or $\theta_s = \theta$ if it is assumed approximately normal to the chord line.

### 2.2 Ship responses with the effects of flapping wing

The preceding analysis, in conjunction with Eqs.(2.1) and (2.2), permits us to calculate the ship responses including the effect of the flapping wing operating as an unsteady thruster and stabilizer, and compare with the corresponding seakeeping responses concerning the bare hull without the wing. For the horizontal flapping wing (Fig.1) in head waves, the normalized heave response of the ship with respect to the incident wave amplitude ($\xi_{30} / A$) is plotted in Fig.2(a), as calculated by the present method, for various values of the non-dimensional wavelength ($\lambda / L$) and Froude number

$$F_{ship} = U / \sqrt{gL} = 0.25 \quad (U=5.5m/s).$$

The modified response obtained due to the operation of the horizontal flapping wing is shown by using a thick solid line. We observe a significant reduction of the ship heaving motion, especially in the vicinity of the resonant condition (indicated by using an arrow). This result is due to the damping effect from the operation of the harmonically oscillating wing in flapping.
mode of operation, using $w=0.5$ to control the wing pitching motion with respect to its own pivot axis (cf. Eq. 2.6).

Furthermore, in Fig. 2(b) the same effect concerning the calculated ship-pitch response $(\xi_{50}/kA)$ is presented. We can clearly observe in this figure that the operation of the flapping wing propulsor, shown again by using a thick solid line, leads to significant reduction of pitch ship response, and especially for all frequencies corresponding to wavelengths longer than the ship length. The noticeable reduction of the above ship responses is also evidence of significant energy extraction from the waves by the present unsteady thruster. We finally denote that an extra effect, strongly connected with the reduction of ship responses due to the flapping wing, is the expected drop of the added wave resistance of the ship. Indicative results concerning the latter additional benefit are given in Belibassakis & Politis (2013).

3 PERFORMANCE IN RANDOM WAVES

In the present work, the free-surface and the random incident waves are directly taken into account concerning the performance of the system operating in head random waves. Also, the transfer function from sea wave spectra to energy spectra of vertical foil motion is based on the Response Amplitude Operator (RAO) of the system at the exact longitudinal location of the wing.

3.1 Random multichromatic waves

For the formulation of the incident waves the standard random phase model is used; see Pierson (1952) and Longuet-Higgins (1952). Details can also be found in Ochi (1998). To illustrate the effect of random waves and vertical motion of the foil on its performance, a 2D panel method is developed to numerically model the flapping foil in finite submergence. The solution is compatible with unsteady linearised theory at low amplitudes and frequencies, and provides satisfactory comparisons with experiments at higher amplitudes and frequencies, as well as with RANS solvers for the cases of low and medium angles of attack and large Reynolds numbers (Filippas & Belibassakis 2013, 2014). The present method is two dimensional and its extension to three dimensions will be examined in future work. We assume that the slope of the incident waves is small, permitting as to use the linear wave theory. The incident wave field is represented by frequency spectra that correspond to different sea states. The realization of random incident wave elevation is

$$ \eta(x,t) = F(t) \sum_{i=1}^{N_R} \alpha_i \cos(k_i x - \omega_i t + \psi_i), \quad (3.1) $$

where $F(t) = 1 - \exp\left(-f_0^2(t/T)^2\right)$ is a filter function permitting smooth transition from rest to the fully developed state of wave excitation and $N_R$ is the number of discrete frequencies. In this work the Bretschneider model spectrum is used

$$ S(\omega_i) = \frac{1.25 \omega_m^4}{4 \omega_i^3} H^2 \exp\left(-1.25 \frac{\omega_m^4}{\omega_i^4}\right), \quad i = 1, \ldots, N_R, \quad (3.2) $$

where

$$ \omega_i = \Delta \omega (i - 0.5) + \omega_{\min}, \quad \Delta \omega = \frac{\omega_{\max} - \omega_{\min}}{N_R}, \quad (3.3) $$

and $\omega_m$ denotes the spectrum modal circular frequency. $T_m = \frac{2\pi}{\omega_m}$ is the corresponding modal (peak)
period and \( H_s \) denotes the significant wave height.

The angular-frequency range \([\omega_{\text{min}}, \omega_{\text{max}}]\) is the essential support of the spectral density. The wave numbers \( k_i \) and the corresponding wave lengths \( \lambda_i = 2\pi \lambda i \) are connected with the frequencies through the dispersion relation

\[
\omega_i^2 = k_i g \tanh(k_i H),
\]

(3.4)

where \( g \) is the acceleration of gravity and \( H \) is the constant (finite) water depth. The modal wavelength \( \lambda_m \) and wave number \( k_m \) can also be obtained from the dispersion relation at the modal frequency \( \omega_m \).

The independent random variables \( \psi_i, i=1,...,N_R \) are uniformly distributed in \([0, 2\pi]\), and the amplitudes are given by

\[
a_i = \sqrt{2S(\omega_i)\Delta\omega}.
\]

(3.5)

Finally, the multichromatic incident wave potential is modeled as follows

\[
\Phi_i(x,y,t) = F(t) \sum_{i=1}^{N_R} \varphi_i \frac{\cosh(k_i(y+H))}{\cosh(k_iH)} \sin(k_i x - \omega t + \psi_i),
\]

(3.6)

where \( \varphi = g\alpha_i / \omega_i \) are the corresponding potential amplitudes.

### 3.2 Hydrofoil’s motion

We consider a flapping hydrofoil in random wave environment. The hydrofoil starts from the rest and accelerates until a constant forward speed, that corresponds to a Froude number defined as

\[
F_n = U / \sqrt{gc},
\]

where \( U \) is the speed of the foil (with positive values at the direction of the negative x-axis) and \( c \) its chord length. Also, in the present work we consider head waves, therefore the modal frequency of encounter is

\[
\omega_{en} = \omega_m + k_m U.
\]

(3.7)

The incident wave spectrum \( S(\omega) \) at the inertial reference frame is given by Eq.(3.2). We can obtain the expression for the wave spectrum at the moving frame of reference (according to an observer that moves with constant velocity \( \bar{U} \)) using the conservation of energy

\[
S^U(\omega_{en}) = S(\omega) \frac{d\omega}{d\omega_{en}},
\]

(3.8)

where the differential of the absolute frequency can be calculated using Eqs.(3.4) and (3.7)

\[
d\omega = d\omega_{en} \left[ 1 + \frac{2U}{gY} \right],
\]

(3.9)

and

\[
Y = \tanh(kH) + kH \text{sech}^2(kH).
\]

(3.10)

In this way, the spectrum of the heaving motion of the foil with respect to the moving frame of reference can be obtained using the RAO at the exact location of the foil as calculated by the analysis of the previous section

\[
S_{\text{foil}}^U(\omega_{en}) = S^U(\omega_{en}) \|\text{RAO}_{\text{foil}}(\omega_{en})\|^2,
\]

(3.11)

while the phase difference between foil’s heave and the incident wave is given by the argument of the complex \( \text{RAO}_{\text{foil}} \). An example of the above transformation is shown in Fig.3 for a wave spectrum corresponding to sea conditions \( H_s = 4m \) and \( T_m = 10s \). Using the above relation and Eq.(3.8) we can finally obtain the spectrum of the foil’s vertical motion at the earth-fixed frame of reference, and the corresponding simulation can be based on similar expressions as (3.1) with amplitudes based on \( S_{\text{foil}} \).
Furthermore, the rotational (pitching) motion (which is positive counterclockwise) of the hydrofoil is defined with respect to a rotation axis located at distance $x_\theta = c/3$ from the leading edge for minimization of the required torque, see Belibassakis & Politis (2013). That motion is properly controlled as a function of the known random heave history. The control law we apply here had been proposed by Politis & Politis (2012) and were applied by Belibassakis and Politis (2013).

3.3 Formulation of the problem

The studied configuration is depicted in Fig.4. The problem is time dependent and the oscillating body is represented by a moving boundary $\partial D_B(t)$ with respect to the earth-fixed frame of reference. The amplitude of the free surface waves is assumed to be small in comparison with the wave length permitting as a first approximation, linearization of the free-surface boundary conditions on the mean free surface level (shown in Fig.4 by using a dashed line). A Cartesian coordinate system is introduced with y-axis pointing upwards and x-axis on the mean free surface. The total wave potential $\Phi_T(x,y,t)$ consists of the random incident wave potential $\Phi_I(x,y,t)$ which is known from Eq.(3.6) and the disturbance potential $\Phi(x,y,t)$ which satisfies the 2D Laplace equation, supplemented by the body boundary condition

$$\frac{\partial \Phi_B(x,y,t)}{\partial n_B} = b, \quad (x,y) \in \partial D_B,$$

where

$$b = -\frac{\partial \Phi_I(x,y,t)}{\partial n_B} + V_B \cdot \mathbf{n}_B,$$

for $(x,y) \in \partial D_B$, and the bottom no-entrance boundary condition; for details see Filippas Belibassakis (2014). In the above relations $\mathbf{n}$ is the unit normal vector pointing into the interior of $D$. The linearized dynamic and kinematic boundary conditions are satisfied on the mean free surface

$$\frac{\partial \Phi_F(x,y,t)}{\partial t} = -g\eta(x,t) , \quad \text{on } y = 0,$$

$$\frac{\partial \Phi_F(x,y,t)}{\partial y} = \frac{\partial \eta(x,t)}{\partial t} , \quad y = 0.$$  

Figure 4. Flapping hydrofoil (of chord $c$) moving under the free surface (at submergence $d$).

In the above equations $\eta(x,t)$ denotes the free-surface elevation associated with the disturbance field and $g$ the acceleration of gravity. In the case of lifting flow around a hydrofoil, the problem is supplemented by the kinematic and dynamic conditions on the trailing vortex sheet

$$p_w^t(x,y,t) = p_w(x,y,t) , \quad (x,y) \in \partial D_w,$$

$$\frac{\partial \Phi_w^t(x,y,t)}{\partial n_w} = \frac{\partial \Phi_w(x,y,t)}{\partial n_w} , \quad (x,y) \in \partial D_w,$$

stating that the pressure $p_w$ and the normal velocity are continuous through $\partial D_w$. In lifting flow problems, enforcement of the Kutta condition is required, in order to fix the circulation at each time instant. In the present work, a non-linear, pressure-type Kutta condition, requiring zero pressure difference at the trailing edge. More details on the vortex wake model are given in Filippas & Belibassakis (2014).

3.4 Boundary integral formulation

Applying the representation theorem of the potential (Green’s formula, see e.g. Kress 1989) to our problem for points at the body contour and the free surface, respectively, we obtain a system of two equations, one for $\Phi_B$ and another for $\Phi_F$, written compactly as follows

$$\frac{1}{2} \Phi_{BF}(x_0,t) =$$

$$= \iint_{\partial D_B} b(x,t)G(x_0|x) - \Phi_B(x,t) \frac{\partial G(x_0|x)}{\partial n} dS(x)$$

$$+ \iint_{\partial D_b} \frac{\partial \Phi_F(x,t)}{\partial n} G(x_0|x) - \Phi_F(x,t) \frac{\partial G(x_0|x)}{\partial n} dS(x)$$

$$- \iint_{\partial D_w} \mu_w(x,t) \frac{\partial G(x_0|x)}{\partial n} dS(x).$$
In the above relation we have used the Green’s function consisted of the fundamental solution of 2D Laplace equation corresponding to a Rankine source and a mirror source with respect to the bottom surface \( G(x_0 \mid x) = \frac{\ln r(x_0 \mid x)}{2\pi} + \frac{\ln r(x_0 \mid x)}{2\pi} \), where 
\( r(x_0 \mid x) = |x_0 - x| \). \( x_0 = (x_0, y_0) \) is the field point, \( x = (x, y) \) is the integration point and \( x_n = (x, -y - 2H) \) its image with respect to \( \partial D_w \).

The normal derivative on the boundary is easily derived by differentiating. In this way the bottom boundary condition is identified satisfied and the corresponding boundary term of the integral representation is dropped.

The representation theorem (3.18) includes the contribution from the wake surface \( \partial D_w \) in the last integral that introduces a memory effect. Additional memory effects are present due to diffraction and radiation caused by the moving body. Moreover, the contribution of incoming wave potential is included at the right-hand side of the body boundary condition Eq.(3.12). Relation (3.18) will be used to set-up a Dirichlet-to-Neumann map (DtN) of the boundary values concerning \( \Phi_E \) and \( \Phi_B \) and their normal derivatives and also the value of the potential jump or the dipole intensity \( \mu_w \), on \( \partial D_w \) in the vicinity of the trailing edge. The latter, after discretization, will be applied to the numerical integration of the free surface boundary conditions (3.14), (3.15) and the pressure Kutta condition, treated as a dynamical system, with dynamic variables \( \Phi_E, \eta, \) and \( \mu_w \), providing us with the evolution of the unknown free surface at the specified level of approximation.

3.5 The discrete DtN map

Following a low-order panel method the body is replaced with a closed polygonal line (with \( N_B \) denoting the number of panels), while the free surface and the wake are approximated by \( N_F \) and \( N_W(t) \) straight-line panels, respectively. The potential and its normal derivative, the potential jump on the wake, the potential and the elevation of the free surface, at each time step, are approximated by piecewise constant distributions. Applying a collocation scheme using the center of each panel as collocation point, where Eq. (3.18) is satisfied, the following discretization equations are obtained, written in matrix form

\[
A \left[ \begin{array}{c} \Phi_B \\ \Phi_E \\ \end{array} \right] = S \left[ \begin{array}{c} b \\ \Phi_F \\ \end{array} \right] + W\mu_w + W_K\mu_{w1}, \quad (3.19)
\]

In the above equations \( \Phi_B = \{ \Phi_{B,i} \}, \Phi_F = \{ \Phi_{F,j} \}, \]
\( b = \left\{ \frac{\partial \Phi_{B,i}}{\partial n} \right\}, \frac{\partial \Phi_E}{\partial n} = \{ \Phi_{F,j} \}, \mu_w = \{ \mu_{w,j} \} \), \( i, n \in \{1, ..., N_B\}, j, m \in \{1, ..., N_F\}, k \in \{2, ..., N_W(t)\} \).

Also the matrices \( A, S, W, W_K \) are defined in terms of the induced factors \( A_{ij} \) and \( B_{ij} \) that represent the potential at the midpoint of the panel \( i \) due to a unit source or dipole distribution at panel \( j \) respectively, for more details see Filippas & Belibassakis (2014). Multiplying equation (3.19) with \( A^{-1} \) we obtain a formula in the form

\[
\left[ \begin{array}{c} \Phi_B \\ \Phi_E \\ \end{array} \right] = D \cdot \left[ \begin{array}{c} b \\ \Phi_F \\ \end{array} \right] + P(\mu_w) + Z\mu_{w1}, \quad (3.20)
\]

with \( D = A^{-1}S \),

\[
P(\mu_w) = \left[ \begin{array}{c} P_1 \\ P_2 \\ \end{array} \right] = A^{-1}(W\mu_w) \) and \( Z = \left[ \begin{array}{c} Z_1 \\ Z_2 \\ \end{array} \right] = A^{-1}W_K \),

(3.21)

the above mapping is the discrete DtN operator which connects the potential with its normal derivative at each collocation point on the boundaries \( \partial D_B \) and \( \partial D_F \), but also involves the unknown value of the dipole intensity \( \mu_{w1} \) of the first panel in the trailing vortex sheet \( \partial D_y \). We observe in the above equations that the influence of the wake, that introduces memory effects, is taken into account through \( P(\mu_w) \), and the effect of the incident wave through the component \( \partial \Phi_i / \partial n_B \) included in \( b \), as described by the body boundary condition Eq.(3.12).

The nonlinear pressure-type Kutta condition can be put in discrete form as described in more detail in Filippas & Belibassakis (2014). Using the appropriate part of the extended DtN map, Eq.(3.20), in the discrete form of the free-surface boundary conditions Eqs.(3.14)&(3.15) and the discrete pressure-type Kutta condition, we finally obtain the following extended system of ODEs, that approximately describe the dynamics of the system.
\[ \frac{d\mathbf{U}}{dt} = \mathbf{f}(\mathbf{U}), \quad \text{where } \mathbf{U} = \left[ \Phi \quad \eta \quad \mu_w \right]^T, \tag{3.22} \]

where the exact definition of the vector function \( \mathbf{f} \) can be found in Filippas & Belibassakis (2014).

Equation (3.22) can be numerically integrated in order to calculate the evolution of the dynamic variables \( \Phi, \eta, \mu_w \), on the basis of information concerning the functions \( \Phi, \eta, \mu_w \) at previous time steps, in conjunction with the history of the wake dipole intensity \( \mu_w \), included in \( \mathbf{P} \), and the data \( \mathbf{b} = -\frac{\partial \Phi}{\partial n} + \mathbf{V}_h \cdot \mathbf{n}_b \) known at every time step from the incident wave field Eq.(3.6), and the body boundary condition Eq.(3.12).

Starting from a prescribed initial condition, e.g. from rest, a time-stepping method is applied to obtain the solution. After evaluation of different methods we found that the higher-order Adams-Bashford-Moulton predictor-corrector method provides the required accuracy, stability and efficiency. The used scheme requires calculation of only two derivative formulas at each time, and the error is of order \( (\Delta t^3) \), where \( \Delta t \) is the time step, ensuring that good convergence is achieved. An important task concerning the present time-domain scheme deals with the treatment of the horizontally infinite domain and the implementation of appropriate radiation-type conditions at infinity. The present work is based on the truncation of the domain and on the implementation of Perfectly Matched Layer (PML) model. The latter model permits the numerical absorption of the waves reaching the left and right termination ends of the truncated domain, with minimum reflection. More details about the time-integration method, the Stability and convergence of the present scheme as well as the PML absorbing model can be found in Filippas & Belibassakis (2013, 2014).

After the solution has been obtained (at each time step) the pressure can be calculated through the unsteady Bernoulli’s theorem. Furthermore, forces and the moment are directly calculated through the integration of the instantaneous pressure acting on the solid boundary.

4 NUMERICAL RESULTS AND DISCUSSION

In this section numerical results are presented and discussed concerning the performance of a NACA0012 flapping hydrofoil in random wave conditions, at various sea states and a range of the mean submergence and pitch control parameter. The random incident wave field is represented by frequency spectra corresponding to different sea states and the motion of the foil is calculated using the RAO of the ship at the exact location of the foil. We consider various sea conditions labeled by an index ranging from 1 to 5. The correspondence of sea conditions with Beaufort scale (BF), the sea state and the main spectral wave parameters, i.e., the significant wave height \( (H_s) \) and the modal period \( (T_m) \) is given in Table 1.

As a first example we present in Fig.5 the time series of some important quantities relative to the problem of thrust production using flapping hydrofoils in random wave conditions. We present the signals for 15 periods after the third modal period, when the transition from the rest has been completed. We examine a hydrofoil at mean submergence \( d/c = 7 \), Froude number \( Fn = U / \sqrt{g}c = 1 \), in random head waves that corresponds to sea state 4 using pitch control parameter \( w = 0.5 \) and pitching motion with respect to a rotation axis at distance \( X_p = c / 3 \) from the leading edge.

![Figure 5. Evolution of kinematic parameters and integrated hydrodynamic quantities for a NACA0012 hydrofoil in random head waves corresponding to sea state 4 at mean submergence \( d/c = 7 \), for time duration of 15 modal periods. \( Fn = 1 \) and control parameter \( w = 0.5 \).](image-url)
In the upper subplot the time history of heaving motion at the location of the foil (produced by the mixed heaving and pitching motion of the ship) and the calculated lift coefficient \( C_L = F_L / 0.5 \rho U^2 c \) are shown together. We observe that significant amplitudes of the vertical force can be produced. Moreover the phase lag between foil’s motion and lift is approximately 180° and therefore lift acts as a restoring force that reduces the unwanted responses and enhance the stability of a ship equipped with flapping hydrofoils, as we have also seen from RAO calculations using lifting line theory (Fig.2). Also, in the lower subplot we present the evolution of thrust coefficient \( C_T = -F_T / 0.5 \rho U^2 c \). We observe that the thrust oscillations are in the interval \( 0 \leq C_T \leq 1.56 \), having an average value of \( C_T = 0.13 \) which is indicated by using bold red line.

Moreover, in Fig.6 we examine the effect of sea state on the augmentation of the overall propulsion of the ship in random waves. The same parameters as in the previous example are considered, and the significant wave height and the modal period take the values listed in Table 1. We notice that as the wave height and the available environmental energy increases, the value of mean thrust coefficient also increases.

For the same hydrofoil at sea condition 4, and the other parameters as in Fig.5, we examine in Fig.7 the effects of free surface and of the incident waves. In particular, the mean thrust coefficient is shown as a function of the mean submergence to modal wave length ratio. The mean submergence to chord ratio in this figure varies in the interval \( 7 < d/c < 40 \). We can see that the effect of free surface is to reduce the thrust coefficient due to the developed wave resistance, and it is quite important in a wide range of values of the submergence ratio.

Finally, in Fig.8 the effect of the pitch control parameter \( w \) is demonstrated for the NACA0012 hydrofoil in the case examined in Fig.5. With bold line the mean thrust coefficient is plotted as a function of \( w \). We clearly observe that as the pitch control parameter decreases, the calculated thrust coefficient increases, as expected due to the increase of the effective angle of attack. However, the present method provides an underestimation of the thrust coefficient at large angles of attack (see also Filippas & Belibassakis 2014) due to leading edge separation and dynamic stall effects that are not presently modeled. For this reason the root mean square and the maximum value of the angle of attack are also plotted in Fig.8, using circles and triangles, respectively, supporting the selection of the pitch control parameter in order to avoid leading edge separation. The present work can be exploited to derive guidelines concerning the design and optimum control of such systems extracting energy from sea waves for augmenting marine propulsion in rough seas, with
simultaneous reduction of ship responses offering dynamic stabilization (Belibassakis & Politis 2013).

CONCLUSIONS

An unsteady Boundary Element Method, developed by the authors, is applied to the hydrodynamic analysis of flapping hydrofoils operating beneath the free surface, in the presence of incident waves and taking into account the coupling between the hull and the flapping foil dynamics. The possibility of energy extraction with simultaneous reduction of ship responses under random wave operating conditions using active pitch control is demonstrated. More specifically, we consider operation of the foil in head waves characterized by a given frequency spectrum, corresponding to specific sea states. The transfer function from sea wave spectra to energy spectra of vertical foil motion is based on the Response Amplitude Operator (RAO) of the system at the exact longitudinal location of the wing. The effects of the wavy free surface are taken into account through the satisfaction of the corresponding boundary conditions. Numerical results concerning the thrust coefficient are presented, indicating that significant efficiency can be obtained under optimal operating conditions and that the free surface effects are important to the performance of the system and cannot be neglected. Thus, the present method can serve as a useful tool for the preliminary design, assessment and optimum control of such biomimetic systems extracting energy from sea waves and augmenting marine propulsion. Future extensions include the introduction and modeling of various non-linearities associated with the evolution of the free surface and the trailing vortex sheets and dynamic stall effects. Another important direction for future study is the 3D problem of flapping-wing thrusters in waves and finally, the direct coupling with the ship dynamics through the satisfaction of the solid boundary condition on the hull.

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