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Augmenting ship propulsion in waves using flapping foils initially designed for roll stabilization

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Abstract

Biomimetic flapping foils attached on ship hull are studied for wave-energy extraction, stored in ship motions, and direct conversion to propulsive power. We examine a pair of roll-stabilization wings located at the side of the hull, in horizontal arrangement. The fins gain their linear oscillation (heaving) from ship pitching and heaving responses in irregular waves, while wing's rotation (pitching) is properly controlled with respect to its vertical motion history. A method, developed in our previous works, is applied for that purpose. The system operates in realistic sea conditions modeled by using parametric spectra, taking into account the coupling between ship responses and the hydrodynamics of the lifting appendages. We present numerical calculations concerning the operation of the augmenting system indicating that, although the present arrangement is designed for roll reduction purposes it can obtain significant amount of thrust. Also it is illustrated that, after reposition of the fins near the bow, the performance of the system can be further enhanced.

Keywords: *flapping foils, unsteady thruster, free-surface effects, random waves, active control*

1 Introduction

Biomimetic systems such as flapping foils, located on the hull of the ship, are examined for the exploitation of environmental energy stored in ship motions and direct conversion to useful propulsive power. The most frequent situation of ship operation is not the calm sea, due to the excitation from the waves and the wind, the ship performs oscillations of significant amplitude, and some of its motions (e.g. heaving and pitching) can be found exploitable to provide the linear oscillation of an unsteady flapping foil propulsion system without energy demand. At first stage of research, passive flapping wings-systems, attached beneath the ship hull, are tested in order to produce thrust, exploiting energy that is stored in ship motions, with concurrently enhancing ship stability and reducing unwanted responses; see, for example, the works of Rozhdestvensky & Ryzhov (2003) and Naito & Isshiki (2005).

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More recently, Belibassakis and Politis (2013) suggested to replace the passive spring loaded rotation mechanism by simple actively controlled enforced pitch motion, based on the (irregular) history of wing's vertical oscillation. In order to produce thrust, a flapping foil performs a complex motion that can be decomposed to a linear and a rotational oscillation, while it advances with the ship's forward speed. Wing's linear oscillation is provided by ship's irregular motion in rough sea, to be more specific by vessel's heaving and pitching, at the exact station that the system is located. On the other hand, foils rotation is actively controlled on the basis of its vertical motion and it is externally enforced with low cost. They introduced a method for the coupling of ship dynamics with unsteady flapping wing hydrodynamics by using linear seakeeping analysis in conjunction with unsteady lifting-line theory and non-linear 3D panel methods. First stage numerical calculations reveal that wave energy can be extracted from ship motions by flapping-foil propulsors with concurrently reducing ship's unwanted responses, enhancing in this way its stability and the conditions of travelling.

Focusing in the importance of the effects associated with the interaction of the foil with the sea waves and the free surface boundary, Filippas & Belibassakis (2014) developed a two dimensional time domain boundary element method, in order to study the performance of a hydrofoil that performs unsteady motions in the proximity of the free surface, in harmonic waves. Validation of the method has been done through comparison of calculations against linear theory, CFD numerical methods and experiments. Moreover, the significance of the effects of the freely moving boundary over the foil is underlined. Finally, it is demonstrated that the system's performance in harmonic-wave conditions is very promising.

Furthermore, Belibassakis and Filippas (2015), aiming to the investigation of the performance of the system in more realistic irregular waves that corresponds to specific sea states, enriched that novel time-domain method, so as to be able to handle with random motions in random waves, coupling also the ship hull dynamics with foil hydrodynamics, in the same manner as Belibassakis & Politis (2013) suggested. In this way they studied various parameters of the ship-foil system in realistic sea condition, including the effects of foils finite submergence.

In the present work, we apply the aforementioned method, so as to examine a pair of roll-stabilization wings, located at the side of the hull, for energy extraction from the waves and thrust production purposes. The fins gain their linear oscillation (heaving) from ship pitching and heaving responses in irregular waves, while wing's rotation (pitching) is properly controlled with respect to its vertical motion history, producing positive thrust and augmenting ship's overall propulsion.

2 Ship dynamics coupled with unsteady flapping-foil thruster

We consider a ship in head waves advancing at constant forward speed U. In the present approach, we use the equations of motion of the ship, derived in the body-fixed frame of reference and linearized by assuming small oscillatory amplitudes and small-slope free-surface waves. We apply a classical linear seakeeping method, in the frequency domain, to calculate the coupled heaving (ξ_{30}) and pitching (ξ_{50}) responses of the system (ship and foil) in the vertical plane; see also the previous work of Belibassakis and Politis (2014). The system of the equations that describe the dynamics of the system is as follows:

$$D_{33}\xi_{30} + D_{35}\xi_{50} = F_{30} + X_{30} \quad \& \quad D_{53}\xi_{30} + D_{55}\xi_{50} = F_{50} + X_{50}, \tag{2.1}$$

where

$$D_{33}=\left(-\omega_{en}^{2}\left(m+a_{33}\right)+i\omega_{en}b_{33}+c_{33}\right),\quad D_{35}=\left(-\omega_{en}^{2}\left(a_{35}+I_{35}\right)+i\omega_{en}b_{35}+c_{35}+p\right), \tag{2.2a}$$

$$D_{53}=\left(-\omega_{en}^{2}\left(a_{53}+I_{53}\right)+i\omega_{en}b_{53}+c_{53}\right),\quad D_{55}=\left(-\omega_{en}^{2}\left(a_{55}+I_{55}\right)+i\omega_{en}b_{55}+c_{55}\right), \tag{2.2b}$$

where a_{jk} and b_{jk}, $j,k=3,5$, are the complex added mass and damping coefficients, *m* is the total mass of the ship and the wing and $p=-i\omega_{en}Um$ is a Coriolis term. Concerning the elements of the hydrostatic matrix we have $c_{33}=\rho g A_{WL}$, $c_{35}=c_{53}=-\rho g\left(x_f A_{WL}\right)$ and $c_{55}=m\,g\,GM_L$. Also we have the following moments of inertia $I_{55}=mR_{yy}^2$ and $I_{35}=I_{53}=-m\,X_G$, where X_G is the longitudinal position of the center of gravity and R_{yy} the radius of gyration with respect to the transverse axis. In this work we study bow waves, therefore the encounter frequency is $\omega_{en}=\omega+kU$, where k is the wavenumber of the incident waves and ω is the frequency with respect to an inertial observer, *g* is the acceleration of gravity and *U* the vessel speed. Also, with $F_{j0}, j=3,5$ we represent the Froude-Krylov and diffraction force and moment complex amplitudes, respectively. While, the coupling with flapping wing dynamics is done through the terms $X_{j0}, j=3,5$, that denote excitation due to the lifting appendages. That forces and moments are functions of heaving $\left(\xi_3\right)$ and pitching $\left(\xi_5\right)$ responses of the ship, depending also on the incident wave-field.

In the sequel we will briefly describe the approach that is used in order to analyze the wing forces and moments and more details can be found in our previous work (Belibassakis & Filippas, 2015). Beginning with the kinematics of the flapping foil, the effective angle of attack is approximately given by the following expression:

$$\alpha(t)\approx-\xi_5(t)+\varepsilon(t)+\frac{1}{U}\frac{\partial\varphi_{INC}}{\partial z}-\theta(t), \tag{2.3}$$

with $\theta(t)$ we denote the angle of rotation of the foil. Also, we have the effect of wing's linear oscillation to the angle of attack $\varepsilon(t)\approx\dfrac{1}{U}\dfrac{dh(t)}{dt}$, where $h(t)=-\xi_3(t)+x_{wing}\xi_5(t)$ denotes the oscillatory motion of the ship at the longitudinal position x_{wing} of the foil. Following the work of Politis & Politis (2014) wing rotation is selected to be a linear function of the angle ε, i.e. $\theta(t)=w\varepsilon(t)$, and the multiplier *w* is call pitch control parameter. Therefore, we finally obtain the following formula for the angle of attack

$$\alpha(t)=-\xi_5(t)+(1-w)\,\varepsilon(t)+\frac{1}{U}\frac{\partial\varphi_{INC}}{\partial z}, \tag{2.4}$$

If we assume large aspect ratio, unsteady lifting line theory can be used to analyze foil excitation. In the present work, under the additional assumption of small Strouhal numbers, the calculation of forces is based on a quasi-steady approximation and spanwise integration of sectional lift forces, resulting in the following expressions

$$X_{30}=\frac{1}{2}\rho U^2 S_w\,C_L^{3D}\approx\frac{1}{2}\rho U^2 S_w\frac{AR}{AR+2}C_L^{2D}=G\alpha_0+\frac{Gc_R h_0}{4U^2}\omega^2+X_{30,B}\left(\varphi_{INC}\right), \tag{2.5}$$

$$X_{50} = \frac{1}{2}\rho U^2 c_R S_w \; C_M^{3D} - \frac{1}{2}\rho U^2 S_w C_L^{3D} x_{wing} \approx -x_{wing} X_{30} \,, \tag{2.6}$$

where c_R denotes the root chord of the foil, $X_{30,B}\left(\varphi_{INC}\right)$ is the contribution of the incoming wave and $G = \chi\, \pi\rho U^2 S_w \frac{AR}{AR+2}$. In the latter expression, χ denotes an empirical correction factor that could be calculated by comparing the quasi-steady lifting line estimations with a-posteriori predictions by more accurate time domain panel methods for the responses of the oscillatory wing, following the same combined forward and oscillatory motion (see, e.g., Belibassakis & Politis 2014).

Applying the aforementioned analysis in the dynamic system Eqs. (2.1) and (2.2), we introduce the following variations to the system coefficients at the left hand side, due to the operation of the flapping foil :

$$\delta a_{33} = -Gc_R / \left(4U^2\right) \,, \quad \delta a_{35} = \delta a_{53} = x_{wing} G c_R / \left(4U^2\right), \quad \delta a_{55} = -x_{wing}^2 G c_R / \left(4U^2\right). \tag{2.7}$$

$$\delta b_{33} = G\left(1-w\right)/U \,, \quad \delta b_{35} = \delta b_{53} = -G\left(1-w\right) x_{wing} / U \,, \quad \delta b_{55} = G\left(1-w\right) x_{wing}^2 / U \,. \tag{2.8}$$

$$\delta c_{35} = G \,, \qquad \delta c_{55} = -G\, x_{wing} \,. \tag{2.9}$$

Furthermore, we obtain the next set of expressions concerning the incident wave-field dependent forces $\boldsymbol{X}_B\left(\varphi_{INC}\right)$:

$$X_{30} = G\left(i\omega / U\right) \exp\left(-kd + ikx\right), \tag{2.10a}$$

$$X_{50} = -G\, x_{wing}\left(i\omega / U\right) \exp\left(-kd + ikx\right), \tag{2.10b}$$

where the vertical location of the foil beneath the free surface is expressed by $z = -d$.

3 Performance in random waves - Hydrofoil motion

Using the responses of the system, the kinematics of the flapping wing are obtained, permitting the detailed formulation and study of the performance of the wing sections operating in random head waves. For this reason, the 2D panel method developed by Filippas & Belibassakis (2014) is applied to analyze numerically the performance of 2D hydrofoils beneath the free surface. As a first approximation we use the assumption of waves with small amplitude in comparison with the wavelength and we work in the context of linear free surface wave theory. Realistic sea conditions are modeled by using parametric spectra and the realization of the free surface elevation and of other wave signals is implemented by using the classical random phase model, more details can be found in the latest work of Belibassakis and Filippas (2015)

The final speed of the foil *U*, reached after acceleration from rest, is connected with the following Froude number $F_{foil} = U / \sqrt{gc}$ based on the chord *c* of the foil. We denote with $S(\omega)$ the wave spectrum in the earth fixed frame of reference and we can obtain an expression for the spectrum according to a moving observer with the foil mean velocity *U*, as follows

$$S^U(\omega_{en}) = S(\omega)\frac{d\omega}{d\omega_{en}} \,, \text{ with } \; d\omega = d\omega_{en} \Big/ \left(1 + \frac{2U}{gY}\right), \text{ and } \; Y = \tanh(kH) + kH\,\mathrm{sech}^2(kH)\,, \tag{3.1}$$

then we use the response amplitude operator *RAO* at the position x_{wing} of the wing, in order to obtain the spectrum of wings linear motion

$$S^{U}_{foil}(\omega_{en}) = S^{U}(\omega_{en}) \left| RAO_{foil}(\omega_{en}) \right|^{2}, \tag{3.2}$$

Furthermore, the rotational motion of the hydrofoil, about an axis at $x_R = c/3$ distance from the foils leading edge, is defined as negative at the clockwise direction. The latter self-pitching motion of the foil is a result of a simple active control law as discussed in the previous section based on its linear oscillation history (Politis & Politis, 2014 and Belibassakis & Politis, 2014).

3.1 Boundary value problem of the flapping foil beneath the free surface in waves

In this section the 2D BEM, developed by Filippas and Belibassakis (2014), is applied to obtain the performance of flapping wing sections operating in random head waves, propagating in constant depth *H*. The problem is treated in time domain and the flapping hydrofoil is denoted with a closed boundary $\partial D_B(t)$ moving with respect to an earth fixed reference frame. As we have already mention, we work at first stage, in the context of linear wave theory and the total wave potential $\Phi_T(x,y;t)$ is decomposed to the incident irregular wave potential $\Phi_I(x,y;t)$, and its disturbance due to the operation of the foil $\Phi(x,y;t)$. We reformulate the problem with respect to the disturbance potential that ought to satisfy Laplace equation. Furthermore, on the solid boundaries the following, no entrance Neumann condition, should be satisfied

$$\frac{\partial \Phi(x,y;t)}{\partial n_B} = b \ , \ (x,y) \in \partial D_B , \quad \text{where} \quad b = -\frac{\partial \Phi_I(x,y;t)}{\partial n_B} + \boldsymbol{V}_B \cdot \boldsymbol{n}_B , \tag{3.3}$$

and the corresponding bottom boundary condition; more details are provided in our previous work (Filippas & Belibassakis, 2014). Moreover, classical linear free surface boundary conditions are applied on the mean free-surface level. In all equations, with $\boldsymbol{n}$ we denote the normal to the boundary unit vector, directed to the interior of the domain D.

In order to treat lifting flow problems around bodied with sharp boundaries like the trailing edge of a hydrofoil, a vortex wake model must be used in order to model the generation of lift on the foil and the introduction of vorticity on the wake. In the present work a curve of potential discontinuity is generated behind the foil and a simplified wake model is used. The trailing vorticity model, as well as the implementation of a pressure-type Kutta condition on foil's trailing edge, are described in detail in our previous work (Filippas Belibassakis, 2014).

3.2 Boundary integral representation and BEM

The present boundary value problem is treated by means of boundary integral equation theory. Applying Green's theorem, the following set of boundary integral equations (one for the body boundary and one for the free surface boundary) is obtained, with unknowns the potential on the body boundary Φ_B and on the free surface Φ_F, as well as their normal derivatives

$$\frac{1}{2}\Phi_{B/F}(\boldsymbol{x}_0;t) = \iint\limits_{\partial D_B} b(\boldsymbol{x};t)G(\boldsymbol{x}_0 \mid \boldsymbol{x}) - \Phi_B(\boldsymbol{x};t)\frac{G(\boldsymbol{x}_0 \mid \boldsymbol{x})}{\partial n} dS(\boldsymbol{x}) +$$
$$+\iint\limits_{\partial D_F} \frac{\partial \Phi_F(\boldsymbol{x};t)}{\partial n} G(\boldsymbol{x}_0 \mid \boldsymbol{x}) - \Phi_F(\boldsymbol{x};t)\frac{\partial G(\boldsymbol{x}_0 \mid \boldsymbol{x})}{\partial n} dS(\boldsymbol{x}) - \iint\limits_{\partial D_W} \mu_W(\boldsymbol{x};t)\frac{\partial G(\boldsymbol{x}_0 \mid \boldsymbol{x})}{\partial n} dS(\boldsymbol{x}), \tag{3.4}$$

where with $G(\boldsymbol{x}_0 \mid \boldsymbol{x})$ we denote the 2D Laplace Green function, that also includes the mirror of the source singularity with respect to the bottom surface ($y = -H$), in order to satisfy the horizontal bottom boundary condition:

$$G(\boldsymbol{x}_0 \mid \boldsymbol{x}) = \frac{\ln r(\boldsymbol{x}_0 \mid \boldsymbol{x})}{2\pi} + \frac{\ln r(\boldsymbol{x}_0 \mid \boldsymbol{x}_m)}{2\pi}, \quad r(\boldsymbol{x}_0 \mid \boldsymbol{x}) = \left|\boldsymbol{x}_0 - \boldsymbol{x}\right|, \tag{3.5}$$

where $\boldsymbol{x}_0 = (x_0, y_0)$ denotes a control point, $\boldsymbol{x} = (x, y)$ is the integration point and $\boldsymbol{x}_m = (x, -y-2H)$ its image with respect the horizontal bottom.

Applying a low-order boundary element method we replace the body contour with a polygonal curve of N_B straight line elements, and also the boundaries of the free surface and of the vortex wake are represented by N_F and $N_W(t)$ elements, respectively. The various hydrodynamic quantities on the panels such as the potential, its normal to the boundary derivative, are assumed to be piecewise constant. Moreover we use a collocation scheme with control points the center of each panel and we obtain the following discretised form of Eq. (3.4)

$$\begin{bmatrix} \boldsymbol{\Phi}_{\mathrm{B}} \\ \dfrac{\partial \boldsymbol{\Phi}_F}{\partial n} \end{bmatrix} = \boldsymbol{D} \cdot \begin{bmatrix} \boldsymbol{b} \\ \boldsymbol{\Phi}_F \end{bmatrix} + \boldsymbol{P}(\boldsymbol{\mu}_W) + \boldsymbol{Z}\mu_{W1}. \tag{3.6}$$

In the above formula the vectors $\boldsymbol{\Phi}_B$, $\boldsymbol{\Phi}_F$, $\boldsymbol{b}$, $\dfrac{\partial \boldsymbol{\Phi}_F}{\partial n}$ and $\boldsymbol{\mu}_W$ consist of hydrodynamic quantities at collocation points of each boundary and the matrixes $\boldsymbol{D}, \boldsymbol{P}, \boldsymbol{Z}$ are calculated as functions of panel integrals, that in the case of low order panel methods can be calculated analytically. Eq.(3.6) is the discrete Dirichlet to Neumann (*DtN)* operator, that relates the potential with its derivative on the boundary, and also includes the unknown value of the potential jump or the dipole intensity μ_{W1} on the wake at the vicinity of the trailing edge.

Applying the discrete *DtN* map, Eq.(3.6), in the discretized form of the pressure-type Kutta condition and the free surface conditions we derive a system of ODEs that governs the evolution of the dynamical system in time, within the context of our approximation,

$$\frac{d\boldsymbol{U}}{dt} = \boldsymbol{f}(\boldsymbol{U}) \text{ where } \boldsymbol{U} = \left[\boldsymbol{\Phi}_F \;\; \boldsymbol{\eta} \;\; \mu_{W1}\right]^T. \tag{3.7}$$

More details concerning the analytic formula of the $\boldsymbol{f}$ operator and the numerical method for the time integration, as well as details for the numerical treatment of the horizontally infinite boundary can be found in our previous work (Filippas Belibassakis, 2014).

4 Numerical results and discussion

In this section, we present a feasibility study on a patrol boat that is equipped with two fin stabilized near the midship section for roll reduction purposes. Although the design of wings with small span located near the pitch rotation centre of the ship is optimal for roll reduction and not for extraction of energy from ship motions, we would like to examine if that the existing set up can perform as flapping wing propulsor only by changing the control law of the wing's rotational motion. The main dimensions of the ship are: length L=61.9m, breadth B=9.5m, draft T=2.5m, block coefficient C_b=0.42. The displacement in salt water is Δ=550tn. Moreover, the wetted surface is calculated S_{wet}=478m^2, the waterplane area A_{WL}=475m^2, the flotation-center x_f = -4.85m (LCF aft midship), the longitudinal moment of inertia is I_L=110000m^4, and the corresponding metacentric radius BM_L=179 m. The vertical position of the buoyancy center is KB=1.65m (from BL), and its position on the horizontal axis is LCB=-2.856m. We assume that the horizontal position of the gravity center is the same as the location of the center of buoyancy, i.e. X_G=-2.856m (aft midship), Y_G=0, and KG=4.05m (from BL). Furthermore, the longitudinal metacentric height is $GM_L \approx BM_L$. Finally, the radii of gyration about the x-axis and y-axis, respectively, are taken R_{xx}=-3.3, R_{yy}=13.13. The foil is located at a distance x_{wing}=-5m, with respect to the midship section, and vertically d=2.5m below WL. The half-wing planform shape is trapezoidal and its span is s=1.5m. Moreover, the root and tip chords of the wing have lengths c_R=1m, c_T=0.5m, respectively. The wing planform area is S_w=4.5m2, and its aspect ratio AR=2. The wing sections are symmetrical NACA0012.

Numerical calculations are presented considering the vertical motion of the hydrofoil in head waves, which is described by the combined ship hull – flapping foil responses. The flapping foil is located at mean submergence $d/c = 2.5$, advancing with velocity U, that corresponds to large Froude number $F_{foil} = U/\sqrt{gc} = 3.83 \left(F_{ship} = 0.49\right)$, in irregular waves of sea state 4-5. Calculations have been done by using pitch control parameter $w = -0.5$ and setting the pivot-axis of the self-pitching motion of the flapping foil at distance $c/3$ from the leading edge. The hydrofoil is located near the pitch rotation center of the ship, at distance x_{wing} =-5m with respect to the midship section of the ship.

We present in Fig.1 the time series of important quantities concerning thrust production by the examined system, operating in random wave conditions, as calculated by the present method. In the first subplot we present the time history of foil's heaving motion, as produced by combined oscillatory heaving and pitching motion of the coupled ship-flapping foil system, together with the generated lift coefficient $C_L = F_Y / 0.5\rho U^2 c$. We observe that significant amplitudes of the lift force are produced. Moreover, the phase lag between foil's motion and lift force is approximately $180°$ and therefore, the generated lift acts as a restoring force reducing the responses of a ship equipped with flapping hydrofoils. In the second subplot the dynamic evolution of thrust T is shown, in the same time interval. We observe in this subplot that the thrust oscillations are in the interval $0 \le T \le 7150kp$, with an average value of $956kp$, which is indicated by using thick solid line. That thrust production is important and in the case of the present existing system that is not optimized for energy extraction. Moreover, in the third subplot the power extracted by the examined system from the waves is compared against the corresponding power that is necessary for the self-pitching motion of the foil, actually for tuning the instantaneous angle of attack in order to produce positive thrust. A dashed line is used to indicate the achieved propulsion power. In the same subplot a bold line is used to indicate the power required for the self pitching motion of the foil, which is negligible.

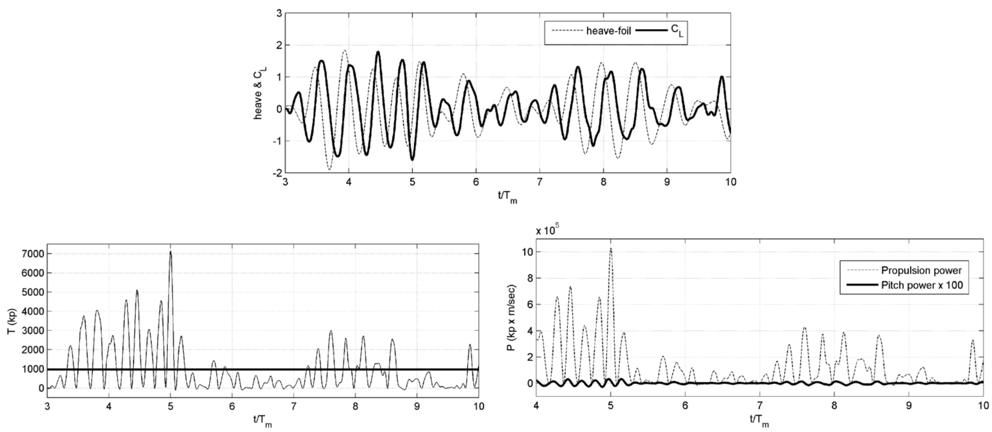

Figure 1: Evolution of motion and integrated hydrodynamic quantities for a NACA0012 flapping hydrofoil in random head waves, corresponding to sea state 4-5, travelling at $F_{foil} = 3.83$, for time duration of 7 modal periods. Foil mean submergence $d/c = 2.5$ and control parameter $w = -0.5$.

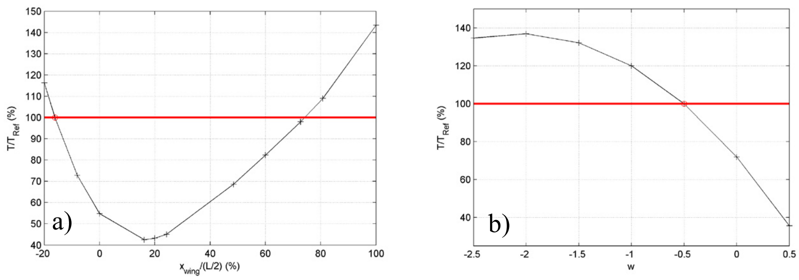

Figure 2: a) Thrust as a function of longitudinal position of the foil x_{foil}, normalized using the thrust obtained when $X_{foil} = -5\,\text{m}$. b) Thrust as a function of pitch control parameter w, normalized using the thrust obtained when $w = -0.5$.

For the same conditions as in Fig.1, the effect of the longitudinal position of the flapping wing is demonstrated in Fig.2 a). In this plot the mean thrust is plotted against x_{wing} measured from the midship section and expressed as a portion of ship half length *L/2*. The thrust is also normalized using the thrust obtained when $X_{foil} = -5\,\text{m}$ indicated by using red thick line. As it is expected, best position for thrust production is not the existing one, but near the bow or the stern of the ship and therefore, with proper variation on the design of the existing system more energy can be extracted and directly transformed to thrust more efficiently.

Finally, in Fig.2 b) the effect of the pitch control parameter *w* on the thrust production by the flapping foil is investigated. In particular, the mean thrust coefficient is plotted as a function of w using a thick solid line. Wave conditions and foil data are kept the same as in Fig.1. We clearly observe that as the pitch control parameter is getting smaller, the calculated thrust coefficient increases, as expected, due to the increase of the amplitude of the effective angle of attack. However, the present method does not provide very reliable predictions of the thrust coefficient at large angles of attack due to dynamic stall effects, which are not presently modeled and that is the reason that for the present feasibility study we have made a conservative selection of $w = -0.5$ and not even lower values that would probably led to larger thrust production.

Conclusions

The concept of biomimetic flapping foils for energy extraction and augmentation of ship prolusion is been explored. More specifically on the present work we focused on the possible performance of roll-stabilization wings, operating as unsteady thrusters. A mixed frequency-time domain method, developed in our previous works is applied for that purpose. Linearized ship dynamics coupled with unsteady lifting line theory is used, in order to obtain the response of the ship-foil system, in irregular waves that correspond to specific sea states. After we have obtained the kinematics of the wing, an unsteady time domain boundary element method has been applied for the hydrodynamic analysis of flapping foils beneath the free surface, in the presence of irregular incident waves. Numerical results concerning the thrust production have been presented, demonstrating the possible application of roll-reduction systems, for energy extraction from the waves and the augmentation of ship's overall propulsion. Furthermore, it is illustrated that with appropriate redesign of the location of the fins the performance of the system can be further enhanced. Future work is focused on the enrichment of the present method and the improvement of its accuracy to the direction of the incorporation of non linear effects connected with the free surface dynamics and the leading edge separation. Furthermore, full treatment of 3D effects is important for studying various additional parameters including the effects of directional seas and the geometry of wings with more sophisticated design and lower aspect ratio.

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