ABSTRACT

Environmental conditions corresponding to realistic sea states (which can be rarely considered calm) significantly affect ship propulsion due to added wave resistance, wind resistance and other factors, as e.g., continuous rudder motion for steering in adverse conditions. In addition, external factors such as ocean currents, which determine the actual flow on the ship, critically affect the actual behavior of the propulsion system. All the above cause significant additional energy losses that sometimes could drive the propulsion system of a ship at its limits. On the other hand, the operation of ship propellers and thrusters in real sea conditions is quite different from their design specifications, usually considered in calm conditions. For example, the vertical stern motion of the ship significantly affects propeller efficiency and becomes dramatically worse if emergence of propeller occurs in high waves. Operation of the ship propulsion system in random waves causes significant variations in performance. In this work we examine in detail the effects of wave-induced motions of the ship on the modification of propulsive thrust and efficiency. Our analysis is based on the non-linear Unsteady Boundary Element Modeling Code UBEM which is applied for the analysis of an unsteadily moving propeller in a wake field, in conjunction with seakeeping analysis in regular and irregular waves. Results from the present hydrodynamic analysis, in conjunction with predictions of added resistance, are used to illustrate applicability in the case of an AFRAMAX tanker, investigating the benefits of small regulation of ship speed and engine RPM from the point of view of optimizing ship’s propulsive performance and reduction of energy losses. The present analysis could support the development of ship monitoring and decision support systems, integrated with engine control systems, aiming to maximize operating efficiency in realistic sea conditions.

1. INTRODUCTION

Requirements and inter-governmental regulations related to vehicle technology for reduced pollution and environmental impact (e.g., Kyoto treaty) have become strict, and response to the demand of greening of transport has been recognized to be an important factor concerning global warming and climatic change. On the other hand, the efficiency and economy of shipping against land and air transport, supports the growth of the fleets. The important role of shipping is clearly underlined by the fact that, today, about 90% of the world trade is being transported by ship. Thus, environmentally friendly technical solutions with reduction of exhaust gases are requested. Additionally, the increased competition in the field of maritime technology requires even more economical vessels. Therefore, minimization of ship resistance/drag reduction has become a central issue.

The wave resistance of a ship can be reduced by model testing and systematic application of modern design Computational Hydrodynamics tools; see, e.g., ITTC [1-3]. The frictional resistance of a ship may be reduced by injection of micro bubbles, using air films and polymers, super water repellent coatings, magneto hydrodynamics and surface shaping; details can be found in ITTC ([2], sec.8.5). However, the ships rarely operate in calm sea, and in realistic sea states and adverse conditions additional components come into play, as e.g. added wave and wind resistance, as well as the effect of ship’s stern motion on the propeller-hull interaction. Moreover, propellers and ship hulls get fouled. Recent studies, Muntean [4], report achievable gains of ship energy losses of the order of 5% by exploiting accurate sensing to better control the propulsion train.
In this work we examine the effects of ship wave-induced vertical oscillatory motion on the propeller’s thrust production and efficiency, calculated by means of a non-linear Unsteady Boundary Element Modeling code UBEM applied for the analysis of a propeller operating in ship’s wake and undergoing motion as part of the ship stern, Politis [5-7]. Results from the present analysis, in conjunction with predictions of the added resistance obtained by strip theory and the radiated energy method, (see, e.g. Arribas [8]), are then used to illustrate applicability to the case of an AFRAMAX 105000tn DWT tanker, for which various data are available concerning ship hull form, general arrangement and load conditions, as well as engine data and ship performance for various speeds, including information about shaft RPM, thrust and torque, environmental conditions etc.

The present analysis could be found useful in supporting the development of ship and fleet monitoring systems integrated with engine and control systems aiming to maximize operating efficiency and optimize ship’s planning of docking for hull cleaning and propeller polishing.

2. SHIP & PROPELLER DATA

The present analysis concerns an AFRAMAX class tanker with length between perpendiculars $L_{BP} = 234\text{ m}$ and 105000tn DWT; see Fig.1(a). The main dimensions and principal data of this ship are: $L = 238.5\text{ m}$ (overall length), $B = 42\text{ m}$ (max breadth), $T = 14.9\text{ m}$ (scantling draft). In the full load condition ($T=14.9\text{ m}$) the main hydrostatic data are displacement $\Delta = 122770\text{ tn}$, $C_B = 0.81$, $KB = 7.76\text{ m}$. The center of gravity is located at $KG = 12\text{ m}$, $LCG = 6.8\text{ m}$, the metacentric height is $GM = 6.1\text{ m}$, and the radii of gyration about transverse and longitudinal axes passing through the center of gravity are estimated to be: $R_{yy} = 63\text{ m}$, $R_{xx} = 12\text{ m}$. Using the main dimensions, in conjunction with the basic geometrical data, hydrostatic quantities and weights, a three dimensional NURBS model of the hull has been reconstructed, as shown in Fig.1(b). For the reconstructed ship model, the calculated hydrostatic diagram is illustrated in Fig.2(a).
Also, the static stability curve corresponding to the full load condition \( T=14.9 \text{m} \) is shown in Fig.2(b). For this ship information concerning bare-hull calm-water resistance was available as it was estimated from model tests at various drafts. Extrapolation of these data to full scale are shown in Fig.3 concerning the full load condition \( (T=14.9 \text{m}) \) and a second draft of the examined AFRAMAX tanker, \( T=13.6 \text{m} \). In addition, data concerning the distribution of the axial wake \( 1-w = U_A / V_s \) on the propeller plane is available as shown in Fig.4. From this plot we observe a strong variation of incoming flow with azimuthal angle, especially around the top position \( (\theta=0\text{deg}) \). The global wake fraction has been estimated by self propulsion tests, and at \( T=14.9 \text{m} \) draft is \( 1-w = 0.645 \). The above wake data refers to calm water conditions and presents small variation for ship speeds in the interval \( 13-15 \text{kn} \) and ship drafts in \( 12.5-15 \text{m} \), and for the needs of the present study these data are considered to be fixed.

Also, information concerning the propeller of this ship is available. The ship is equipped with a single 4-bladed propeller \( (z = 4) \), of diameter \( D = 7.2 \text{m} \), and expanded area ratio \( A_e = 0.5 \). The reference pitch ratio of the propeller blades at \( r/R = 0.7 \) is \( P/D = 0.695 \). Furthermore the blade rake is zero and the tip skew is \( \theta_s = 18.75^\circ \). This low-pitch propeller has been designed as a wake adapted one, based on the circumferentially mean axial wake calculated at various radii from the data of Fig.4. Moreover, thrust deduction and relative rotative efficiency have been estimated from experiments to be \( 1-t = 0.770 \) and \( \eta_r = 1.037 \), respectively.
Figure 6. Open water characteristics of the propeller model of Fig 5, as obtained by the present UBEM using a discretization 17 spanwise by 22 chordwise elements.

Figure 7. Time history of propeller thrust (negative values) and torque coefficients (a) wavy line: unsteady thrust/torque in viscous wake, (b) dashed line: mean-one-turn value of (a), (c) straight line: calculated results in open water conditions for advance coefficient J=0.396 corresponding to steadily translated ship with forward speed $V_s=14\text{kn}$ and 97RPM propeller revolutions.

From the latter data the hull efficiency is estimated to be $\eta_h=1.19$. As before the above values present relatively small variation and thus, in the present study these interaction coefficients are treated as speed independent. From the available data a discrete boundary element model of the propeller is constructed using a grid of 17 spanwise elements, as shown in Fig.5. The open water characteristics are calculated using UBEM. Results concerning the thrust and torque coefficients $K_t=T/\rho n^2 D^4, K_q=T/\rho n^2 D^5$, (where $n$ denotes the propeller rps and $\rho$ is the water density) and the open-water efficiency over the range of advance coefficients $J=A_U/nD$ are presented in Fig. 6. Details concerning the calculation methodology including blade section drag corrections can be found in Ref. [4], sec.2.3. As an example, we present in Fig. 7 the time history of the propeller thrust (negative values) and torque coefficients. More specifically figure 7 shows: (a) wavy line: unsteady thrust/torque in viscous wake, (b) dashed line: mean-one-turn value of (a), (c) straight line: calculated results for open water conditions corresponding to the mean viscous wake velocity (corresponding J=0.396). On the basis of the overall mean wake $1-w=0.645$, the previous value of the advance coefficient corresponds to ship speed $V_s=14\text{kn}$ and propeller revolutions 97RPM (1.61rps). For the operation of the examined propeller in the ship’s wake we observe in Fig.7 an oscillation of the propeller thrust and torque with strong first-harmonic in blade frequency $f=6.46\text{Hz}$. The average values of developed thrust and torque, after some propeller revolutions (ensuring that the transient phenomena due to the starting effects are died out) are plotted by using dashed lines in Fig.7. We clearly observe that the mean propeller trust increases while the mean torque presents small variation from the corresponding values in open water. Calculated values are listed in Table 1, where we observe that the mean propeller efficiency is increased by 2.8% and that the amplitudes of oscillatory

<table>
<thead>
<tr>
<th></th>
<th>open water</th>
<th>in the wake of Fig.4</th>
<th>blade freq. amplitude/mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_t$</td>
<td>0.169</td>
<td>0.179</td>
<td>12.2%</td>
</tr>
<tr>
<td>$10K_q$</td>
<td>0.187</td>
<td>0.189</td>
<td>10.5%</td>
</tr>
<tr>
<td>efficiency</td>
<td>56.9%</td>
<td>59.7%</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Propeller performance data, in open water and in the wake of Fig.4, for J=0.396 (mean).
thrust and torque in blade frequency are of the order of 12-10% of the corresponding average values.

The examined ship is equipped with one Diesel engine (MAN B&W 6S60MC type, MCR 15400BHP @ 97RPM), directly coupled to the propeller. The engine is capable of driving the ship (clean hull) at about 14.2kn, in calm water and scantling draft loading condition (T=14.90m), with a sufficient power margin for real sea conditions. Based on the above propeller analysis and results, the behavior of the propulsion system based on the calm-water resistance for the above propeller analysis and results, the behavior of the propulsion system based on the calm-water resistance for the two drafts $T=7.2m$ (dotted line) and $T=14.9m$ (continuous line) is calculated, and the results are plotted in Fig.8.

In the following, we will consider and present seakeeping results concerning the AFRAMAX tanker permitting us (i) to obtain predictions of added resistance of the ship in the examined full load condition in waves, and (ii) information concerning the vertical stern motion at the propeller plane, for various sea-states. The former information, in combination with calm water resistance data (Fig.3) at ship’s speed, open-water propeller data (Fig.6) at propeller revolutions, and propeller-hull hydro-dynamic interaction coefficients, will finally provide us an estimation of the shaft thrust and torque, from the point of view of the force and power required to overcome total resistance in real sea-states. It is noted here that wind action and rudder motion (and perhaps also other factors) contribute to the total ship resistance, however these components have been considered of secondary importance in comparison to calm-water and wave-added resistance and are left to be included in future extensions of the present approach.

On the other hand, the vertical ship motion at the propeller location induced by the waves and the wave velocity field on the propeller plane could be used, in conjunction with shaft rpm, ship’s speed and the axial wake distribution of Fig. 4, in unsteady propeller analysis calculations using UBEM, enabling the direct estimation of the propeller mean, unsteady and vibratory forces and moments, as well as efficiency that is directly connected to fuel consumption. Both approaches will eventually enable us to obtain a picture of the behavior of the ship and its propulsion system. Except of drawing conclusions concerning predictability of the present method and its applicability to support ship and fleet monitoring systems, also useful information and data are derived supporting further examination of short- and long-term trends of the difference between the two above predictions. Such a trend, if observed and consistently repeated (in similar future long time intervals), could be an evidence that other factors have come into play, for example an indication of increased hull and propeller fouling effects.

3 SEakeeping ANALYSIS

An important factor concerning ship operation in realistic sea-states, closely connected to ship dynamics, is added resistance in waves. This could also have a strong economical effect on ship exploitation. There are not many simple methods to obtain the added resistance in waves of a ship, and the validity of the results obtained by each method is not always good enough for different types of ships. In a recent work (Arribas [8]), several available methods are studied and validated against seakeeping tests of some monohull models, focusing on head seas, that is usually the most severe situation concerning added resistance. The analysis shows that radiated energy method (Gerritsma & Beukelman [9]) is a method leading to relatively good-quality results in many cases, although it could present numerical stability problem in short waves. In the present study we employ the radiated energy method, as extended by Loukakis & Sclavounos [10] for the prediction of head-to-beam seas, in conjunction with strip theory (Salvesen et al [11]), for the calculation of the added resistance and the vertical ship motion at the stern; see also Lewis ([12 Sec. 3.4). As concerns the added mass and damping coefficients of various ship sections, as well as the Froude-Krylov and diffraction forces, a low-order hybrid panel method, as described in Belibassakis [13], Sec.4, is used to calculate the involved 2D potentials. This method is based on domain decomposition in conjunction with boundary integral formulation based on simple source distribution for the representation of the wave potentials in the near field middle subdomain containing the section, and normal-mode expansions of the potentials in the two semi-infinite strips. The formulation is completed by means of matching conditions, ensuring continuity of all the potentials on the vertical boundaries separating the three subdomains. Although the present analysis is for the ship floating in deep water, the main advantage of the previous hybrid method is its applicability also to cases of limited water depth, permitting us to obtain seakeeping analysis results also in areas of finite depth, either constant or presenting variation along the transverse direction. This could be important in cases of ship operation in areas of limited waterdepths (as e.g. in some routes in the Baltic sea) and/or in channels, where the effects of water depth and its side variation (or ship routes parallel to coastline and bottom contours) on added resistance and ship motions could be important, similarly as happens to be the case with the calm water resistance, and especially for high-speed ships near critical conditions; see, e.g., Suzuki et al [14].

Numerical results concerning the AFRAMAX tanker are presented in Table 1 concerning the mean added resistance, for various ship speeds, from $V_g = 13-14kn$, corresponding to Froude numbers $F=0.14-0.15$, respectively, in head waves ($\beta=180^\circ$). We consider the responses of the system operating at various sea conditions labelled 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 peak period ($T_p$) is given in Table 2. Also, the Bretschneider model spectrum (see, e.g. Ochi [15]) is used for calculations. Our results indicate, in the case of the most severe sea conditions considered, an increase (due to head waves) of the calm-water resistance, at ship speeds in the above interval, of the order 50%-60%, which is quite significant. Moreover, the variation of the mean added resistance with the relative wave direction has been studied for the present ship, as shown in Fig. 9. Results in the interval $90^\circ < \beta < 180^\circ$ are calculating by using the approach by Loukakis & Sclavounos [10]. We observe in Fig.5 that, for low seas (sea condition $\leq 5$), where the peak wavelength to ship length ratio $\lambda_p/L < 1$, the max added resistance is observed in head- to-beam seas ($\beta \approx 150^\circ$).
<table>
<thead>
<tr>
<th>Sea condition</th>
<th>BF</th>
<th>Sea state</th>
<th>Hs(m)</th>
<th>Tp(sec)</th>
<th>Added Resistance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vs =13kn</td>
<td>Vs =14kn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4-5</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>2.2% 1.6%</td>
</tr>
<tr>
<td>3</td>
<td>5-6</td>
<td>4-5</td>
<td>3</td>
<td>9</td>
<td>2.9% 7.1%</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>25.4% 21.5%</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>11</td>
<td>56.1% 47.6%</td>
</tr>
</tbody>
</table>

Table 2: Mean added Resistance (% of calm water resistance at same ship speed at draft T=14.9m), in head waves (β=180°) vs. sea condition and ship speed Vs.

Figure 9. Effects of relative direction of incident waves on the mean added resistance, for various sea conditions.

Figure 10. RAO (modulus and phase) of vertical stern motion against the non-dimensional wavelength (λ/L) and the absolute angular frequency (ω₀).

Figure 11. Wave spectrum for sea condition 4 in earth-fixed and ship frame of reference and stern vertical motion spectrum.

Figure 12. Stochastic simulation for \( V_s = 14kn \) (\( F=0.15 \)) at sea condition 4 (\( H_s = 4m, T_p = 10s \), head waves).
In more severe sea conditions corresponding to greater peak periods $T_p$, where $\lambda_p / L \geq 1$, the added resistance is maximum for head waves ($\beta \approx 180^\circ$).

Results in the interval $0^\circ < \beta < 90^\circ$ (following-to-beam seas), where strip theory fails to provide reasonable predictions for added resistance (that is however insignificant for the AFRAMAX case), are obtained by extrapolating and matching the above distribution with empirical relations; see, e.g., Rosander & Bloch [16]. The effect of the calculated mean added resistance on the propulsive performance characteristics of the ship for dead waves and sea conditions 4-5 is added in Fig.8 by using red line. For max engine and propeller revolutions 97RPM we observe a substantial increase of SHP due to added resistance and a drop of the corresponding ship speed from $V_s = 14kn$ to $V_s = 13kn$.

Moreover, numerical seakeeping analysis results concerning the vertical ship motion at the stern (propeller position) are presented in Fig.10, for head incident waves. In this figure, for the ship at the max draft $T=14.9m$ and speed $V_s = 14kn$ ($F_s = 0.15$), the Response Amplitude Operator (RAO) associated with absolute vertical stern motion is plotted against the non-dimensional wavelength ($\lambda/L$) and the absolute angular ($\theta_{0b}$). The corresponding frequency of encounter is given by

$$\omega = \omega_o - (\omega_o^2 / g) V_s \cos \beta$$  

(1)

in terms of the absolute wave frequency $\omega_o$, ships speed $V_s$ and wave direction $\beta$. From Eq. (1), the spectral density vs. relative frequency is obtained as follows,

$$S(\omega) = S(\omega_o) \left(1 - 2 (\omega V_s / g) \cos \beta\right)^{-1}$$  

(2)

where, as already discussed the Bretschneider model spectrum is used for $S(\omega_o, H_s, T_p)$. Indicative results concerning head waves at sea condition 4 are shown in Fig.11, where also the calculated spectrum of vertical stern motion is plotted based on RAO of Fig.10.

4 UNSTEADY PROPELLER ANALYSIS USING UBEM

The problem of simulating the flow around a propeller undergoing a general 3D motion, as part of a moving ship, while operating in a ship viscous wake, is extensively discussed in Politis [6]. This development has further been extended in Politis [7] where an Unsteady Boundary Element Modeling environment (UBEM) has been presented, capable of treating complex multi-body unsteady flow problems including biomimetic propulsor flows. Furthermore the treatment of the free wake produced by lifting bodies has been improved by using mollifiers instead of cutoffs used initially. For the completeness, a brief presentation concerning the underlying methodology and basic equations used in UBEM is given in the following. The propeller is considered operating in an unbounded fluid. The motion of the propeller’s origin

$$\mathbf{R}(t) = (X(t), Y(t), Z(t))$$  

is prescribed in the inertial (earth-fixed) frame of reference, as well as the instantaneous orientation of the axes of the body-fixed frame of reference, described by the rotation angles

$$\mathbf{\Theta}(t) = (\theta(t), \psi(t), \chi(t))$$

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig13.png}
\caption{Consecutive positions of propeller in a time period of 13s as calculated by the MPP, shots taken every 0.27s.}
\end{figure}

In the present work we consider a general path characterized by the propeller advance with the ship (steady translation), in conjunction with the induced vertical stern motion of the ship in waves, as predicted by the above seakeeping analysis (shown in the middle subplot of Fig. 12). Also, the propeller is assumed to steadily rotate with angular velocity $\Omega = 2\pi\text{RPM}/60$ about its own axis and performing pitching oscillations due to the motion of the ship in waves. Therefore, in the present case

$$X(t) = V_s t, \quad Y(t) = 0, \quad Z(t) = \text{vertical stern motion}$$

$$\theta(t) = \Omega t, \quad \psi(t) = \tan^{-1}(2Z(t)/L), \quad \chi(t) = 0.$$  

With the motion of the propeller known, a special MPP (Motion Preprocessor Program) is applied, which calculates the consecutive propeller positions in time, for an earth reference observer, as shown in Fig. 13. With this information known, UBEM can easily calculate the velocity $\mathbf{v}$ due to the motion of the propeller at each point $(P)$ of the boundary elements constituting the propeller blade surface (see also Fig.5).

On the basis of the above, the no-entrance boundary condition at point $P$ on blade surface has the form:

$$\nabla \cdot \phi \cdot \mathbf{n} = \mathbf{q} \cdot \mathbf{n}$$  

(3)

where $\phi$ denotes the perturbation potential due to propeller operation and $\mathbf{n}$ the unit normal vector to the blade surface at point $P$ and $\mathbf{q} = \mathbf{v} - \mathbf{w}$. Moreover, $\mathbf{w}(x,t)$ represents the disturbance of the incoming flow to the propeller due to ships viscous wake (as shown in Fig.4) and any other factors. As additional factors we consider in this work the effect of wave velocities on the propeller plane, calculated from the total wave field, including incident diffraction and radiation components due to ship heaving and pitching motion, in the ship frame of reference. With the aid of equation (3) the integral equation for the perturbation potential becomes, Politis [7]):

$$\frac{1}{2} \phi(P) = \frac{1}{4\pi} \int_{SB(t)} \phi \frac{\mathbf{n} \cdot r}{r^3} dS - \frac{1}{4\pi} \int_{SK(t)} \mu \frac{\mathbf{n} \cdot r}{r^3} dS =$$

$$= -\frac{1}{4\pi} \int_{SB(t)} \frac{\mathbf{n} \cdot q}{r} dS + \frac{1}{4\pi} \int_{SK(t)} \frac{\mu \mathbf{n} \cdot r}{r^3} dS, \quad P \in SB(t),$$  

(4)

where $r = |\mathbf{r}|$ is the distance between field point and
integration point, $SB(t)$ is the body (propeller blades) surface, $SK(t)$ the Kutta strip surface and $SF(t)$ the free shear layer surface at time $t$. In addition, \( \mu = \phi^+ - \phi^- \) denotes the surface dipole distribution simulating the vorticity on the free shear layers (trailing vortex sheets).

Let the point \( P \in SB(t) \) and \( \frac{dp}{dt} \) denotes the time derivative for an observer at the point $P$ on the propeller. Then, the unsteady version of Bernoulli's equation used in the present work to calculate pressure and forces has the form:

\[
\frac{p-p_w}{\rho} = -\frac{d\phi}{dr} - \frac{1}{2}(\nabla \phi - \mathbf{q}(P))^2 + \frac{1}{2}\mathbf{q}(P)^2, \tag{5}
\]

where $p_w$ is the pressure of the background field in the absence of propeller disturbance.

According to pressure-type Kutta condition, the pressure should be continuous, as the trailing edge point is approached from either pressure side (superscript $+$) or suction side (superscript $-$) of the blades,

\[
p^+ = p^- \tag{6}
\]

Using Eq.(5), the above condition becomes a quadratic (nonlinear) equation involving $\phi^+, \nabla \phi^+, \phi^-, \nabla \phi^-$. The code UBEM materializes equation (6) as a nonlinear pressure type Kutta at the trailing edges of the lifting bodies, which is solved by invoking a Newton iteration method. Furthermore, the code allows the use of mixed-type Kutta conditions, i.e. partially Morino-type (e.g. at propeller blade tips) and partially pressure type. For further discussion and more details see Politis [7].

The kinematic and dynamic conditions on a free (trailing) vortex sheet, expressed in terms of the dipole intensity of the sheet, result in the following equation, Politis [6,7],

\[
\frac{D_{\mu}}{Dt} = 0 \tag{7}
\]

where $D/Dt$ denotes the material derivative for $\mu$ on $SF(t)$ based on the mean velocity of the shear layer. The latter quantity is denoted by $> v <$ and can be found on points of the shear layer as follows

\[
> v < = q_v + \frac{\nabla \phi^+ + \nabla \phi^-}{2}, \tag{8}
\]

where the velocity term $q_v = q_v(t)$ denotes a correction of the free shear layer geometry due to viscous wake and other factors. Thus relation (7) becomes:

\[
\frac{\partial \mu}{\partial t} + > v < \cdot \nabla \mu = 0. \tag{9}
\]

Equation (9) informs us that the dipole surface $SF(t)$ with intensity $\mu(\xi, \eta)$ is travelling with velocity $> v <$ on the trailing vortex sheets, where $\xi, \eta$ denotes a set of curvilinear surface coordinates for the points on $SF(t)$. Thus, if a $\mu$ surface is known at time $t$, we can find its new position, at time $t + dt$, by deforming it by $> v < dt$; see also Katz J. Plotkin, [17]. Notice that formula (8), for the calculation of $> v <$, becomes infinite at the boundary of shear layer $\partial SF(t)$, which significantly influences the vortex rollup process, and has to be treated with caution in numerical calculations. Furthermore, it is connected with Kelvin-Helmholtz instability of trailing vortex sheets, inherently present in such type of problems. For the previous reasons calculation of $> v <$ requires special attention as discussed in detail in Politis [7].

Solution of the present problem is implemented by invoking a time stepping algorithm as described below. At each time step, UBEM:

1. Reads the next position of the system of bodies which is calculated by a GPP/MPP (Geometric Preprocessor Program, Motion Preprocessor Program; see Politis [7]).
2. Generates corresponding Kutta strips $SK(t)$, in the case of lifting bodies, introducing thus the extra unknowns required for the satisfaction of the pressure Kutta condition (6).
3. Solves the system consisting of the “no-entrance” and “Kutta” conditions on $SB(t)$ and $SK(t)$. In case of pressure type Kutta a Newton iteration is used at this step.
4. Deforms the free shear layers (trailing vortex surfaces) to their new positions by applying a special filtering technique to calculate $> v <$, Eqs. (8) and (9).
5. Output results (pressures, forces, velocities, position of free shear layers) for this time step.
6. Proceeds to the next time step and repeats the calculation from step (1).

As an example of the present approach, numerical results are shown in Figs. 14-15, for the AFRAMAX tanker in a particular sea condition corresponding to $H_s=4$m, $T=10s$ (condition 4), head waves ($\beta=180^\circ$), ship speed $V_s=14$kn, and 97RPM propeller revolution rate. More specifically, in Fig. 14 the initial development of the calculated wake of the propeller blades is plotted for a time interval of about 15 sec, where the propeller has performed about 25 complete revolutions. The time step used for computations corresponds to a turn of the propeller blades by an azimuthal angle of 8deg. Except of steady advance and rotation, the propeller motion includes a component due to waves, which has been estimated from the stochastic simulation of the ship motion in the particular sea condition, as also shown in the middle subplot of Fig.12. The effect of disturbance of the otherwise helicoidal propeller motion due to waves is clearly illustrated in Figures 13 and 14. Figure 14 is a snapshot corresponding to the first 15sec of propeller operation starting from an assumed state of rest, and thus it includes also the initial development and expansion of the starting vortex pattern. Except of the effect of general propeller motion in waves, also the effect of the viscous ship wake distribution of Fig.4 has been included in the computations. Moreover, the incident wave velocity on the propeller blades contains an additional component due to waves estimated from the stochastic simulation using the wave spectra corresponding to the examined condition in conjunction with the seakeeping responses of the ship.

More detailed results concerning the calculated thrust and torque of the propeller operating at the above condition, for
the time interval of 15sec, is presented in Fig.15. In the top subplot of Fig.15 the vertical stern motion of the ship in the examined time interval is shown. In the middle subplot the calculated time-history of the thrust coefficient ($K_t$) is plotted, as well as a short-term mean value (shown by using dashed value), obtained by averaging over several time steps. Similarly the time history of the calculated torque coefficient ($10K_q$) is shown in the last subplot of Fig. 15. We clearly observe in this figure the effect of propeller unsteady vibratory loads at the blade frequency (which in the examined case is 6.5Hz). The latter are found again to be of the order 10-12% of the mean values of thrust and torque, in compatibility with the corresponding predictions of the propeller performance in the ship viscous wake of Fig.4, which are indicated at the right-end of these subplots by using red lines. Corresponding results are presented in Fig.16, for the ship operating at the same as before sea wave conditions, but now for somewhat reduced ship speed $V_s = 13kn$ and propeller revolutions 89RPM. The latter values have been approximately estimated using the propulsion performance diagram (see Fig 8) and taking into consideration the effect of added wave resistance.

We note here that, due to the increase of ship responses for somewhat lower Froude number (Fr=0.14) from the previously examined case), the vertical motion of the ship stern and the propeller motion are more pronounced, although same as before wave conditions have been assumed. We clearly observe in these figures that the propeller wave induced vertical motion, in conjunction with the perturbation of the incident field on the propeller blades, due to waves incident on the ship, in addition to the diffracted and radiated component, substantially modifies the propeller performance, and especially the integrated thrust and torque characteristics. These variations are now of the order of 20-25% of the mean propeller loads, and are indicated in Figs.15 and 16 by using arrows. Moreover, the average values of thrust and torque over some wave periods are now different from the previously calculated values at the same operating conditions for the propeller without consideration of the wave effects (as, e.g., listed in Table 1 for J=0.396). We conclude from these results that knowledge of these and similar propeller quantities, in conjunction with information on the added wave resistance, could be useful for developing control methods, aiming to maximize real-time operating efficiency, particularly in more severe sea states.

Currently used predictions of the wave added resistance, as listed in Table 2 for the examined ship, are based on using frequency domain analysis tools and thus, these values correspond to short-term mean values, i.e. mean values considered over time intervals of the order of many characteristic wave periods. Future plans are focused on coupling time-domain seakeeping analysis codes providing real-time predictions of the ship motion and the wave added resistance (see, e.g., Refs. [18,19]) with the propeller performance scheme described in this work. This is especially important concerning the added resistance associated with short waves, which is not predicted by simplified models not accounting for wave diffraction. This will enable a more realistic simulation of the system, including the effects of waves and ship motion on the propeller performance, providing us also useful information concerning extra excitation of longitudinal (surge) motion and additional data for engine performance and consumption optimization. Also,
present method could be applied to calculation of side forces due to effect of oblique wave inflows into the propeller disk.

5 CONCLUSIONS
In this study we have examined the effects of waves and wave-induced vertical motion at the stern of the ship on the propeller operational characteristics, obtained by means of a non-linear BEM for unsteady propeller analysis. Results, including predictions of the added wave resistance, obtained by strip theory and the radiated energy method, are then used to illustrate applicability to the case of an AFRAMAX 105000tn DWT tanker. The present analysis could facilitate development of ship and fleet monitoring decision support systems, integrated with engine and control systems, aiming to maximize operating efficiency and optimize ship planning for docking for hull cleaning and propeller polishing. Future extension of the present work will focus on coupling time-domain seakeeping analysis codes providing real-time predictions of the ship motion and wave added resistance with the propeller unsteady performance modeling code UBEM, enabling a realistic simulation of the ship propulsion system in waves.

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Appendix
In unsteady propeller analysis problems, the term \( w(x,t) \) is usually taken to represent the inhomogeneity due to the ship viscous wake distribution on the propeller vicinity. In the present study, except of the latter component, this term also includes the flow generated on the propeller plane due to waves and ship motions. Assuming that the spectra of various quantities (wave induced motion and velocity) can be calculated short-term time series simulations, with reference to particular sea state \( (H_s,T_p;\beta) \), can be obtained by considering the processes stationary characterized by the narrow band spectrum of the response(s). For example in the case of vertical stern/propeller motion

\[
S_p(\omega) = \int_{\theta} |RAO(\omega,\theta)|^2 S(\omega,\theta;H_s,T_p,\beta) d\theta .
\]  

(A1)

The stochastic simulation of wave velocities in the propeller plane is similarly treated. For simplicity, in the present study the wave spectrum is modeled as a unidirectional one, i.e. \( S = S(\omega;H_s,T_p)\delta(\theta-\beta) \), representing long-crested seas. Subsequently, the random phase model (St. Denis & Pierson [20] and Longuet-Higgins [21]) is applied to obtain a short-term time series of vertical flow velocity on the propeller plane, as follows

\[
Z(t) = \sum_{n=1}^{N} A_n \cos(\omega_n t + \varepsilon_n) ,
\]

(A2)

where \( \varepsilon_n \) are random variables uniformly distributed in \([0,2\pi)\), the amplitudes are given by \( A_n = \sqrt{2S_n} \), and the set of discrete frequencies \( \{\omega_n\} \) are appropriately selected in order to cover the essential support of the spectra and to represent the energy distribution around the peak frequency.