Effects of wave-induced ship motion on propeller-hull interaction with application to fouling estimation and propulsion optimization

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ABSTRACT: In this work we examine the effects of ship wave-induced vertical oscillatory motion on the modification of propeller’s thrust deduction and relative rotative efficiency, obtained by means of a non-linear BEM for unsteady propeller analysis (Belibassakis & Politis 1998, 2002). 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 2007), are then used to illustrate applicability in the case of an AFRAMAX 105000tn DWT tanker, for which continuously measured data are available including ship’s load and speed, shaft RPM, thrust and torque, environmental conditions etc. The present analysis could support 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.

1 INTRODUCTION

In the last period, 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 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 (2005, 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 (see also Kyrtatos et al., 1999). Moreover, propellers and ship hulls get fouled. Recent studies (Muntean 2008) 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 modification of propeller’s thrust deduction and relative rotative efficiency, obtained by means of a non-linear BEM for unsteady propeller analysis (Belibassakis & Politis 1998, 2002). 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 2007), are then used to illustrate applicability to the case of an AFRAMAX 105000tn DWT tanker, for which
continuously measured data are available including ship’s load and speed, shaft RPM, thrust and torque, environmental conditions etc. The data were provided by Thenamaris (Ships Management) Inc, that is gratefully acknowledged.

The present analysis could support 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 & ENVIRONMENTAL DATA

Our study focuses on the case of an AFRAMAX class tanker ship of 234m length (BP) and 105000 tn DWT; see Fig.1, where also rest of main data are listed. For this ship, daily operation data were available spanning a 9-month period from Sept 2007 to May 2008. The recorded data concern ship loading (aft and fwd drafts), ship speed (GPS and Speed Log), weather conditions, including wind relative speed and direction (as well as air temperature and pressure), and engine data, i.e. shaft RPM, in conjunction with shaft thrust and torque. From this data set a subset of about half size was considered in the present study, referring to full-load or almost full-load conditions, with drafts ranging in T=12.5-14.9m. This data set has been filtered out for obvious errors or missing values concerning various recordings and its final usable length was reduced to 97 entries, constituting the long-term time series of the present study.

The above ship is equipped with one Diesel engine (6S60MC type, MCR 15400BHP at 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 10-15% power margin for real sea conditions.

For this ship hydrostatic and stability data are available, as well as bare-hull resistance through model tests at 1/34.715 scale, shown in Fig.2. Also, propeller data are available Fig.3(a), including open-water characteristics as obtained by tests; see Fig.3(b). This low-pitch propeller (with pitch ratio P/D=0.695 at r/R=0.7) has been designed as a wake adapted one, based on the axial flow survey data shown in Fig.3(c). The global wake fraction has been estimated by self propulsion tests, and at scantling draft is \( 1-w = 0.645 \). Moreover, thrust deduction and relative rotative efficiency have been estimated to be \( 1-t = 0.770 \) and \( \eta_R = 1.037 \), respectively. From the above data the hull efficiency is estimated to be \( \eta_H = 1.19 \). As obtained from the
experiments, the above values present relatively small variation for ship speeds in the interval 13-15kn and drafts in 12.5-15m, and thus, in the present study, these interaction coefficients are treated as constants.

In the following, we will consider and present seakeeping results permitting us (i) to obtain predictions of added resistance of the ship in the above loading condition in waves, and (ii) the vertical stern motion at the propeller plane, for various sea-states. The former information, in combination with calm water resistance (Fig.2) at ship’s speed, open-water propeller data (Fig.3) at propeller revolutions, and propeller-hull hydrodynamic interaction coefficients, will finally permit us to estimate 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 with 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 plane could be used, in conjunction with shaft rpm, ship’s speed and axial wake distribution, in an unsteady propeller analysis method, enabling the direct estimation of the propeller mean and vibratory forces and moments. Both approaches will eventually permit us to obtain a picture of the long-term behaviour of the ship and its propulsion system, and compare with measured data concerning thrust and torque, that is directly connected to fuel consumption. Except of drawing conclusions concerning predictability of the present method and its applicability to support ship and fleet monitoring systems, we will be also able to examine the long-term trends of the difference between the two above predictions in the 9-month period spanned by the data. Such a trend, if observed and consistently repeated (in similar future long time intervals), could be attributed to other factors, as e.g., indication of 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 2007), 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, 1972) 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 (1978) for the prediction of head-to-beam seas, in conjunction with strip theory (Salvensen et al 1970), for the calculation of the added resistance and the vertical ship motion at the stern; see also Lewis (1988, 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 (2008, Sec.4), is used to calculate the involved 2D potentials. This method is based on domain decomposition (see Fig.4), in conjunction with boundary integral formulation based on simple source distribution for the representation of the wave potentials in the middle domain $D^{(2)}$, and normal-mode expansions of the potentials in the two semi-infinite strips $D^{(1)}, D^{(3)}$. The formulation is completed by means of matching conditions, ensuring continuity of all the potentials on the vertical boundaries separating the three subdomains (shown by dashed lines in Fig.4). 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 waterdepth, permitting us to obtain seakeeping analysis results also in areas of finite depth, either constant or presenting variation along the tranverse direction (as shown in Fig.4).

Figure 4. Domain decomposition and boundary integral representation in middle domain $D^{(2)}$ containing the bottom (with possible variation) and the floating body.
Table 1: Added Resistance (% of calm water resistance at same ship speed) vs. BF and Vs, for T=14.9m and head waves

<table>
<thead>
<tr>
<th>BF</th>
<th>Uw (m/s)</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
<th>11.5</th>
<th>12.5</th>
<th>13.5</th>
<th>14.5</th>
<th>15.5</th>
</tr>
</thead>
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<td>2</td>
<td>2.0</td>
<td>0.2</td>
<td>2.24</td>
<td>1.31</td>
<td>1.10</td>
<td>0.94</td>
<td>0.57</td>
<td>0.50</td>
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<td>3</td>
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<td>3.93</td>
<td>3.31</td>
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<td>1.71</td>
<td>1.49</td>
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<td>2.49</td>
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<td>8.66</td>
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<td>109.37</td>
<td>92.12</td>
<td>78.39</td>
<td>67.38</td>
</tr>
</tbody>
</table>

Figure 5. Relative direction effects on the added resistance

The latter could be found important in cases of ship routes in limited waterdepths (as e.g. in some routes in the Baltic sea) and/or in channels, where the effects of waterdepth and its side variation (for ship routes parallel to coastline and bottom contours) on added resistance and ship motions could be important, similarly as it 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. (2009).

Numerical results concerning the AFRAMAX tanker of Fig.1 are presented in Table 1, concerning the mean added resistance, for various ship speeds, from Vs=11.5kn-15.5kn, in head waves. Weather conditions are expressed through the Beaufort scale (BF), used for describing sea conditions in terms of wind speed (that was the recorded quantity in our case). The relation used to connect BF with wind speed (Uw), significant wave height (Hs) and peak period (Tp) is provided by the first 4 columns in the above table. A unidirectional JONSWAP wave spectrum (with peak-enhancement parameter γ=3.3) has been used to model the wave spectrum from the above parameters. Our results indicate, in the case of the most severe sea conditions considered (BF8), an increase (due to head waves) of the calm-water resistance, at ship speeds in the above interval, of the order 70%-130%, which is quite significant.

Figure 6. RAO stern relative vertical velocity wrt relative frequency, for various wave directions (β).

Moreover, the variation of the added resistance with the relative wave direction (taken to coincide with the recorded mean wind direction) has been studied for the present ship, as shown in Fig. 5. Results in the interval 90°<β<180° are calculating by using the approach by Loukakis & Sclavounos (1978). We observe in Fig.5 that, for low seas (where the peak wavelength to shiplength ratio λp / L <1), the max added resistance is observed in head-to-beam seas (β ≈−150° to −160°), in contrast with high seas where this happens for head waves. Results in the interval 0°<β<90° (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 (2000).

Moreover, numerical seakeeping analysis results concerning the vertical ship motion at the stern (propeller position) are presented in Fig.6, for various directions of the incident waves. In this figure, for the ship at the scantling draft and speed Vs=14kn (Fn=0.15), the Response Amplitude Operator (RAO) associated with vertical motion relative to the free-surface is plotted, for directions ranging from following waves (β=0°) to beam
\(\omega = \omega_0 - (\omega_0^2 / g)V_s \cos \beta\),

in terms of the absolute wave frequency \(\omega_0\), ships speed \(V_s\) and wave direction \(\beta\). From Eq. (1), the spectral density vs. the relative frequency is obtained as follows

\[S(\omega) = S(\omega_0)(1-2(\omega V_s / g)\cos \beta)^{-1},\]

where, as already discussed, a standard JONSWAP model is used to represent \(S(\omega;H_s,T_p)\).

4 UNSTEADY PROPELLER ANALYSIS

For simulating the unsteady propeller response, a modified version of a velocity based panel method, developed by Belibassakis & Politis (1998, 2002) for the analysis of marine propellers in unsteady flow conditions, is used in the present study. The previous method is based on a boundary integral equation formulation (Fredholm type, second kind), involving surface vorticity distributions (as boundary unknowns) and source distributions, modelling the unsteady marine propeller performance. Pressure type Kutta condition is satisfied along the trailing edge of the blades. The modelling includes hub and finite blade thickness effects.

In accordance with the above formulation, the total velocity field, in the propeller-fixed frame of reference, consists of the following components:

\[\vec{w} = (-\vec{\Omega} \times \vec{x} - \vec{V}_s) + \vec{A}(\vec{x};t) + \vec{v}(\vec{x};t),\]

where \(\vec{x}\) is the position vector, \(-\vec{\Omega} \times \vec{x}\) and \(-\vec{V}_s\) are the relative velocities due to propeller rotation and translation (with ships speed), respectively, and \(\vec{A}(\vec{x};t)\) represents the disturbance of the incoming flow to the propeller due to ships wake and any other factors. Finally, \(\vec{v}(\vec{x};t)\) is the propeller-disturbance velocity field, modelled as an irrotational/incompressible component given by the gradient of propeller disturbance potential:

\[\vec{v}(\vec{x};t) = \nabla_x \Phi(\vec{x};t), \quad \text{in} \quad \Omega_x \setminus S_w\]

where \(S_w\) denotes the trailing vortex sheets and \(\Omega_x\) the exterior (to the propeller) domain.

In unsteady propeller analysis problems, \(\vec{A}(\vec{x};t)\) usually represents the inhomogeneity induced to the translational/rotational motion of the fluid relative to the propeller, due to the ship (effective) wake distribution. This disturbance flow contains, at the leading order, the axial component \(\vec{A}_{aw}(\vec{x};t)\), and at higher orders the corresponding tangential and radial components. In the present study, except of the above, another component \(\vec{A}_{im}(\vec{x};t)\) is included, associated with the flow generated on the propeller plane due to the ship and wave motions. Since the submergence of the propeller is relatively small, as compared with the characteristic (peak) wavelengths of the various sea-states considered, we decided to approximate \(\vec{A}_{im}(\vec{x};t)\) by the time derivative of the relative vertical ship motion at the stern. The latter, at each relative frequency, is obtained from the solution of the seakeeping analysis problem; see Fig. 6. Subsequently, a short-term time series simulation of \(\vec{A}_{im}(\vec{x};t)\), with reference to a particular wave condition \((H_s,T_p;\beta)\), can be obtained, by considering a stationary process characterized by the narrow band spectrum of the vertical motion response

\[S_v(\omega) = \int RAO(\omega,\theta) S(\omega,\theta;H_s,T_p,\beta) d\theta,\]

where \(H_s,T_p,\beta\) stand for the significant wave height, peak period and mean wave direction, respectively. For simplicity, in the present study the wave spectrum is modeled as a unidirectional one:

\[S = S(\omega;H_s,T_p) \delta(\theta - \beta),\]

representing long-crested seas. From the motion spectra the corresponding ones associated with various motion derivatives are easily obtained. For example, the spectrum of the vertical relative velocity is obtained as

\[S_{vM}(\omega) = \omega^2 S_v(\omega).\]

Numerical results concerning a particular sea state (head waves, \(H_s=2m, T_p=7s\)) and for ship speed \(Vs=14kn\) are presented in Fig.7 (left subplot). The calculation concerning the vertical relative velocity spectrum is based on the RAO of the corresponding relative vertical motion, which in this case is also shown in Fig.7 (right subplot).

Subsequently, the model by Pierson (see, e.g., St. Denis & Pierson,1953) and Longuet-Higgins (1952) is applied to obtain a short-term time series of vertical flow velocity on the propeller plane due to ship and wave motions (in ship-fixed coordinates), as follows

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

where \(\varepsilon_n\) are random variables uniformly distributed in \([0,2\pi)\), the amplitudes \(A_n\) are given
Figure 7. Various spectra for the ship at a sea state characterized by $H_s=2\text{m}$, $T=7\text{s}$, $\beta=180^\circ$ and for ship’s speed $V_s=14\text{kn}$ (left). RAO of relative vertical motion at the stern of the ship (right).

Figure 8. Short-term time series of propeller thrust and torque coefficients $K_t$, $10K_q$ vs. the simulated vertical (relative) oscillatory velocity $w(t)$, in the case of the tanker travelling at $V_s=14\text{kn}$, in a sea state ($H_s=2\text{m}$, $T_p=7\text{s}$, $\beta=180^\circ$) and the propeller operating at 92RPM.

by $A_n = \sqrt{2S_{rM}(\omega_n)}\Delta\omega_n$, 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.

On the basis of all the above, the propeller disturbance potential is obtained as a solution to Laplace equation $\nabla^2 \Phi(\vec{x};t) = 0$, in $\Omega_s \setminus S_w$, the no-entrance boundary condition at the various parts (blades/hub/shaft etc) of the solid boundary $\vec{n} \cdot \nabla \Phi(\vec{x};t) = -\vec{n} \cdot (\vec{q}(\vec{x}) + \vec{A}(\vec{x};t))$, combined also with Kutta-type condition, necessitating continuity of pressure along the trailing edge of the propeller blades (and the rest of the blade-edges where flow separation is modelled to occur using vortex sheets). The solution is obtained through the boundary integral equation formulation, automatically satisfying the condition at infinity concerning the propeller induced field $\vec{v}(\vec{x};t)$. 
After the solution is obtained, at each time step, the pressure distribution on the blades and other parts of solid boundaries is calculated by means of a modified Bernoulli’s theorem, of the form

$$\frac{\partial \Phi}{\partial t} + \frac{p - p^{(i)}}{\rho} + \frac{1}{2} \left( \nu \mathbf{v}^2 - \nu \mathbf{w} + \mathbf{A} \mathbf{w} \right) = 0,$$

(8)

where $p^{(i)}$ stands for the onset flow pressure distribution on propeller plane (without propeller interference). In the present case the field $\mathbf{A}$ is composed by

$$\mathbf{A}(\bar{x}; t) = \mathbf{A}_{\text{aw}}(\bar{x}; t) + \mathbf{A}_{\text{vm}}(\bar{x}; t),$$

(9)

where $\mathbf{A}_{\text{aw}}(\bar{x}; t)$ comes from the wake survey data and $\mathbf{A}_{\text{vm}}(\bar{x}; t)$ is obtained from $w(t)$ which is easily converted from the ship-fixed to the rotating frame of reference. Finally, forces and moments and their history are obtained by pressure integration on the blade surfaces. More details can be found in Belibassakis & Politis (1998) and as concerns the corresponding boundary integral formulation in Belibassakis & Politis (1995). We note here that a main difference of the present model with the former works is the addition of a free-wake analysis, based on kinematics and dynamics of free vortex sheets modeled by quadrilateral free vortex rings convected and deformed as they travel downstream the propeller blades with the local flow velocities, similarly as described in Belibassakis & Politis (1997).

As an example of the above approach, numerical results are presented in Fig 8, for the AFRAMAX tanker in a particular sea condition $H_s=2m$, $T=7s$, $\beta=180^\circ$, and ships speed $V_s=14kn$. Specifically, in the last subplot of this figure a small part of the short-term simulation is plotted as concerns the vertical ship motion at the stern $w(t)$, obtained by Eq. (7). In the upper two subplots the corresponding time series concerning the thrust and torque coefficients ($K_t$, $10K_q$) are plotted, for the propeller operating at 92RPM, in the ships axial wake $\mathbf{A}_{\text{aw}}(\bar{x}; t)$, subjected moreover to vertical oscillatory motion $\mathbf{A}_{\text{vm}}(\bar{x}; t)$ calculated from $w(t)$. The result shown in these two subplots is obtained after filtering out the vibratory loads at the blade frequency (which in the case considered is 6.1Hz) and higher harmonics. We note that the overall mean values of the propeller coefficients in this sea/ship condition are $K_t,0=0.186$, $10*K_q,0=0.208$, while the first-order vibratory loads, at the blade frequency are calculated to be $K_t,4=0.012$, $10*K_q,4=0.012$ (as obtained by the 4-th harmonic of the blade forces analysis). The magnitudes of the latter are indicated for comparison in Fig.8 by using thick double arrows. We presume that these high-frequency variations have been filtered out by the measuring

![Figure 9. Long-term time series of mean propeller thrust and torque (solid lines) compared with measured data (thick dashed lines). In the last subplot the calculated difference of propeller thrust obtained from the resistance (including the added resistance) minus the one obtained from the unsteady propeller analysis (including the effect of relative vertical motion at the stern of the tanker) is plotted showing a long-term increase from a level -7.7tn to +2 tn (dashed lines), which could be due to hull fouling.](image-url)
devices (thrust/torque meters), which were installed onboard. On the other hand, we observe in the upper subplots of Fig.8 variations of propeller loads of the order of 5% of the overall mean values that appear at much lower frequency which is practically due to the effect of ship motion on the propeller. This variation, with magnitudes shown in Fig.8 using dotted arrows, if not filtered out by the measuring devices, could introduce uncertainty factors.

Finally, in Fig. 9 (upper two subplots) long-term results are presented concerning the mean thrust/torque history for the 97 entries, constituting the long-term time series data. A comparison is presented between our predictions (solid lines) and measured data (thick dashed lines). Considering the 5% uncertainty levels (as discussed above), we conclude that the predictability of the present method is quite good. In the last subplot of Fig.9 we present the long-term series of the difference between the thrust as predicted by calm water plus added resistance and the thrust from propeller analysis, taking into account ship motion effects. Also in this figure long-term averages corresponding to period of ~4-5 months are shown by using dashed lines. These results indicate a trend for the above difference to increase from -7.7tn to +2tn, that is ~10% of the mean level of the thrust required for driving the ship in the loading condition considered, that could be an indication of hull fouling effect.

5 CONCLUSIONS

In the present study we have examined the effects of ship wave-induced vertical oscillatory motion on the modification of propeller's operational characteristics, obtained by means of a non-linear BEM for unsteady propeller analysis. Results from the present analysis, in conjunction with predictions of the added 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, for which continuously measured data are available including ship’s load and speed, shaft RPM, thrust and torque, environmental conditions etc. It is illustrated that the present method could support 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. The present analysis could also be greatly benefited by expounding simultaneous vertical acceleration measurements (especially at the stern of the ship).

REFERENCES