Computational Evaluation of the Added Resistance in Oblique Seas

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1. Introduction

The increase of the price of fuel shows the necessity to improve the performance of ships in waves. The ship's performance can be tested at the design stage with the simulation of a ship on a given route. This simulation requires information about the calm water resistance, wind resistance, propulsion system and the mean added resistance due to waves for different wave headings.

One of the tools to calculate the mean added resistance in oblique seas is three-dimensional panel codes. They can be divided into two groups. The first group uses a transcient wave source which satisfies the Kelvin free surface condition. Those panel codes (WAMIT, TIMIT, FORCE Technology in-house code S-OMEGA) only need the discretization of the panel hull. The second group uses the Rankine source as the elementary singularity in the boundary integral formulation. Those panel codes (SWAN, SWAN2, AEGIR) need to have both hull and free surface discretized.

The present paper focuses on the estimation of the mean added resistance by the single strength panel code S-OMEGA. S-OMEGA works in the frequency domain and it uses the zero-speed Green function. The effect of the speed is including through the frequency of encounter and the boundary condition at the body. As the zero-speed Green function is used, a correction factor is applied on S-OMEGA results for the added resistance in order to account for the speed effect in short waves. Results are compared with both experimental data and a Rankine source panel code for two ships (S-60 and the container ship S-175) in head and oblique seas. The results show a fair agreement between the corrected S-OMEGA results and the experimental data. For the Series 60, the Rankine panel code shows better results than S-OMEGA at short waves.

2. Theoretical background

2.1 Boundary Value Problem

The vessel is assumed to float in an inviscid, irrotational fluid, with a total flow potential ϕ satisfying the following boundary conditions:

1. Laplace equation, everywhere in the fluid:

$$\nabla^2 \phi = 0 \qquad (1)$$

2. Boundary condition at the horizontal sea bed, h being the water depth:

$$\frac{\partial \phi}{\partial z} = 0 \text{ at } z = -h \qquad (2)$$

3. Linearised boundary condition at the free-surface:

$$\mathbf{U} \cdot \mathbf{U} \cdot \nabla^2 \phi - 2\mathbf{U} \cdot \nabla \left(\frac{\partial \phi}{\partial t} \right) + \frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \qquad (3)$$

where $\mathbf{U}$ is the steady velocity vector of the vessel.

The solution to this boundary condition is a translating, pulsating source. If it is assumed that the speed is low (Fn<<1) and the frequency high ($\frac{U}{L\omega_e}$ <<1), then the free surface boundary condition can be simplified to:

$$\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \qquad (4)$$

which is the same as the zero-speed boundary condition and therefore allows the use of zero-speed Green functions at the appropriate encounter frequency.

4. Sommerfeld radiation condition at infinity:

$$\lim_{r \to \infty} \left[\sqrt{r} \left(\frac{\partial \phi}{\partial r} - \frac{i\omega^2 \phi}{g} \right) \right] = 0 \qquad (5)$$

5. Boundary condition at the body (full reflection):

$$\frac{\partial}{\partial n} \left(\phi_0 + \phi_{nf+1} \right) = 0$$
$$\frac{\partial}{\partial n} \phi_j = n_j + i \frac{\mathbf{U} m_j}{\omega_e}, \; j = 1..nf \qquad (6)$$

In the above the unsteady potential has been split into an incident velocity potential (ϕ_0), a radiated potential (ϕ_i i = 1…6) and a scattered, diffracted velocity potential due to incoming waves on fixed bodies (ϕ_{nf+1}), i.e. the total

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potential is given by:

$$\phi(x,y,z,t)=\phi_0(x,y,z,t)+\phi_{nf+1}(x,y,z,t)+\sum_{j=1}^{nf}\phi_j(x,y,z,t)\cdot\dot{\xi}_j(t) \quad (7)$$

ξ_j *j=1…6* are the motions (relatively surge, sway, heave, roll, pitch and yaw) and m_j are the m-terms defined as $(m_1,m_2,m_3,m_4,m_5,m_6)=(0,0,0,0,Un_3,-Un_2)$ as the Neumann-Kelvin linearization is used.

The ship motions can be obtained by solving the following frequency domain equation:

$$\sum_{j=1}^{nf}\left[\left(m_{ij}+A_{ij}\right)\ddot{\xi}_j+B_{ij}\dot{\xi}_j+C_{ij}\xi_j\right]=F_i e^{-i\omega t},\ \mathrm{i}=1..\mathrm{nf} \quad (8)$$

The m_{ij} terms are the inertial mass terms, A_{ij} are the hydrodynamic added masses, B_{ij} are the hydrodynamic damping coefficients, C_{ij} are the linear restoring force coefficients and F_i are the excitation forces produced by the incident wave field.

2.2 Formulation of Added Resistance

The mean added resistance is evaluated using the pressure integration method. Using Bernoulli's equation and Taylor expansion up to second-order as described in [2], the mean added resistance R_{aw} is as described in Equation (9).

$$\begin{aligned}R_{AW} =& -\frac{1}{2}\rho g\int_{WL}\varsigma_r{}^2\vec{n}dl \\ & -\frac{1}{2}\rho g\iint_{S_{\bar{B}}}\nabla\phi\cdot\nabla\phi\vec{n}dS \\ & -\rho g\iint_{S_{\bar{B}}}\vec{X}_{mot}\cdot\nabla\left[\frac{\partial\phi}{\partial t}-\mathbf{U}\cdot\nabla\phi\right]\vec{n}dS \\ & -\rho\vec{\xi}_R\times M\ddot{x}_g \qquad (9) \\ & -\rho\iint_{S_{\bar{B}}}H\vec{x}\cdot\nabla(gz)\vec{n}dS \\ & -\rho\iint_{S_{\bar{B}}}g\left(z+z_f\right)H\vec{n}dS \\ & -\rho g\vec{\xi}_R\times\iint_{S_{\bar{B}}}\left(\xi_3+\xi_4 y-\xi_5 x\right)\vec{n}dS\end{aligned}$$

ζ_r, ξ_R and $\vec{X}_{mot}$ are the relative wave elevation, the rotational displacement and the total displacement vector respectively. The matrix *H* is a transformation matrix and details can be found in [2].

2.3 Correction of the formulation

As mentioned in paragraph 2.1, S-OMEGA uses the zero-speed Green function and includes the speed through the frequency of encounter and the body condition. However as the frequency gets smaller, using the zero-speed Green function creates a larger and larger error since $\mathrm{U}\omega_e$ is no longer small compared to *g*. It is assumed that this error mainly comes from the mean added resistance from the diffraction potential. In order to reduce the error, a correction factor has been introduced.

According to Tsujimoto et al [4], the mean added resistance from the diffraction potential can be written:

$$R_{AWr}=\frac{1}{2}\rho g\varsigma_a^2 BB_f\alpha_d\left(1+\alpha_U\right) \quad (10)$$

ζ_a and B are the incident wave amplitude and the beam of the ship. B_f is the bluntness coefficient. α_d is a correction factor which includes the effect of draft and frequency. α_U and C_U are defined in Equation (11) and Figure 1.

$$\alpha_U=C_U F_n \quad (11)$$

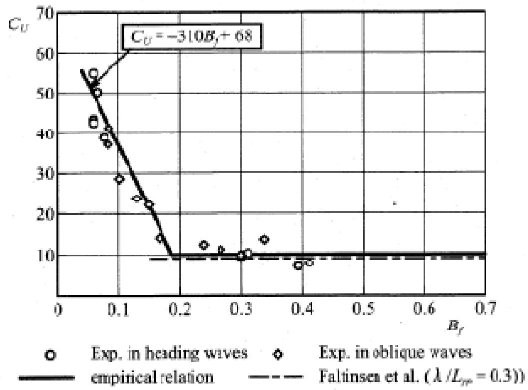

Fig.1 Definition of the C_U coefficient

In S-OMEGA, it is assumed that only the speed dependant part of R_{AWr} is missing. So the total mean added resistance is equal to:

$$R_{AWr}=R_{AW}+\frac{1}{2}\rho g\varsigma_a^2 BB_f\alpha_d\alpha_U \quad (12)$$

3. Results

Two ships have been used to test this method: the Series 60 (C_b=0.7) and the containership S-175.

In this section the added resistance coefficient σ_{AW} is used. It is defined as:

$$\sigma_{AW}=\frac{R_{AW}}{\rho g\zeta_a^2 B^2/L} \quad (13)$$

Results for the Series 60 and the container ship have been compared with respectively experimental data from Strom-Tejsen [5], Vossers [6] and from Fujii [1].

Model	Units	Series 60	S175
L (length)	m	124.18	175.0
B/L (Beam-length ratio)	-	0.143	0.145
D/L (Draft-length ratio)	-	0.057	0.054
kxx (radii of gyration in roll)	-	0.35	0.35
kyy (radii of gyration in pitch)	-	0.25	0.25
KG (vertical distance to center of gravity)	m	6.52	9.65

Table 1: Principal dimensions of the test models

Fig.2 shows the added resistance coefficient calculated with S-OMEGA with and without the correction factor described in section 2.3. Without the correction factor the mean added resistance is too low and becomes negative in short waves. The inclusion of the extra term gives much better results which are closer to the experimental data. In the remaining part of the article, results presented for S-OMEGA include the correction factor.

Fig.3 shows the added resistance predicted by S-OMEGA for the containership S-175 for different wave headings. There is a good agreement between S-OMEGA and experimental data for all headings. In beam seas, S-OMEGA predicted an added resistance lower than the experimental data but the trend is the same. For consistency, the data obtained by the Rankine code were obtained using Neumann-Kelvin linearization (as for S-OMEGA). It appears that the mean added resistance is underestimated around the peak. This behaviour was already noticed with another Rankine panel method as described in [3] where results obtained were better using the double-body flow.

Results from the containership S-175 show that the present method (S-OMEGA) gives good results using Neumann-Kelvin instead of double body flow linearization, which is an advantage given the increase of numerical difficulty with the double-body flow linearization (it uses the derivative of the curvature [2] which can create numerical error).

Fig.4 shows the added resistance for the Series 60 in head and oblique seas. The results are compared with experimental data from Strom-Tejsen [5] in head seas and with Vossers[6] data in oblique seas. For head seas and 170° , there is a small shift between the results obtained with S-OMEGA and the experimental data. S-OMEGA also slightly overpredicts the added resistance in

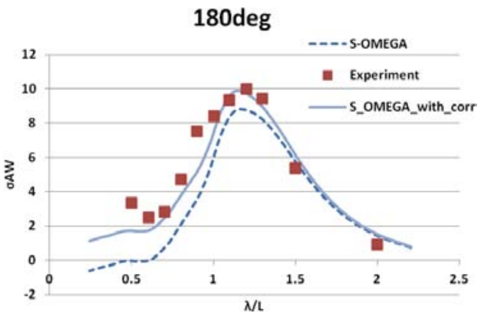

Fig. 2: Influence of the correction factor for the mean added resistance estimated with S-OMEGA for S-175, Fn=0.25

short waves. For these headings, the Rankine code seems to give better results and there is a good agreement between the results from the Rankine panel code and the experimental data at short waves. However at 130° there is a good agreement between S-OMEGA and the experimental data.

In all calculations above, S-OMEGA used the pressure integration method whereas the Rankine code used the momentum conservation method (for convergence reasons). As only the hull needed to be discretized with S-OMEGA, more panels could be used which could explain the good results of the method.

Compared to Rankine panel method, S-OMEGA + correction factor method has the advantage of being fast (it operates in the frequency domain), which is of importance when generating input data for route simulation.

4. Conclusions

The added resistance has been evaluated by combining the results from the frequency domain panel code S-OMEGA with Tsujimoto formula for added resistance in short waves. Results appeared to be in good agreement with experiments for the containership S-175. For the Series 60, results from S-OMEGA were close to experimental data, in spite of a small shift between the two curves. Compared to some Rankine panel code, the method applied by S-OMEGA is fast as it works in the frequency domain and it gives good results using Neumann-Kelvin linearization instead of double-body flow linearization.

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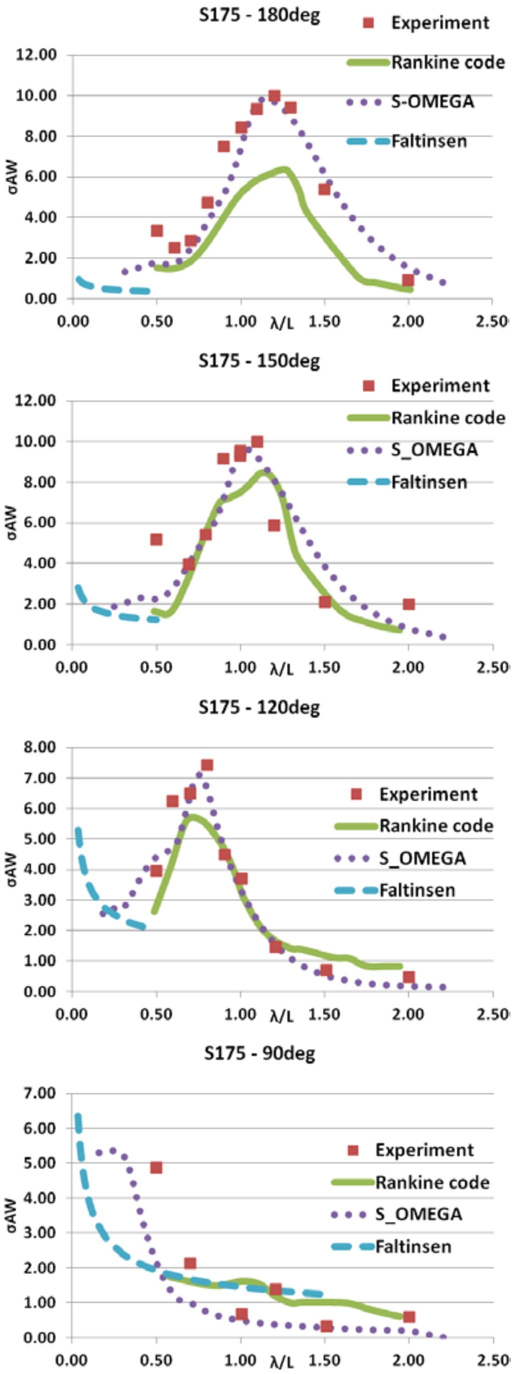

Fig. 3: Mean Added Resistance for the containership S-175 in oblique seas

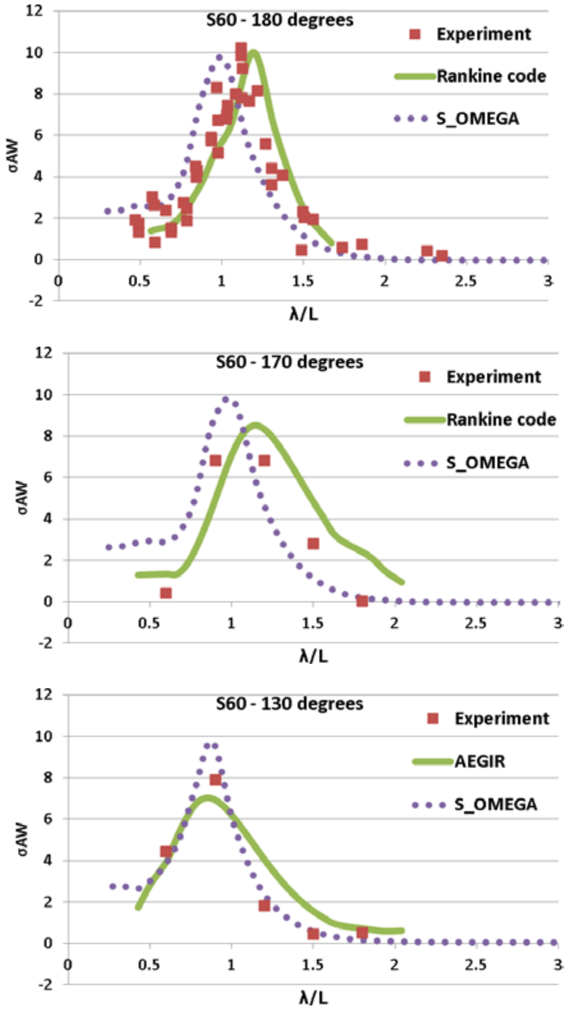

Fig. 4: Mean Added Resistance for the Series 60 in oblique seas

the Danish Center for Maritime Technology.

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