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A BOUNDARY ELEMENT METHOD FOR MOTIONS AND ADDED RESISTANCE OF SHIPS IN WAVES

Summary

The accurate prediction of ship resistance in waves is nowadays of increased importance since it greatly influences ship performance regarding sustainable service speed and fuel consumption in seaways. Added resistance is considered as the longitudinal component of the second order mean force acting on a ship in waves and can be calculated from the first order ship motions by integrating the corresponding second-order pressure on the body surface.

The purpose of this paper is to present a methodology for the prediction of motions and added resistance by a three dimensional Rankine panel method and to discuss and validate its results by comparing them with experimental data. The prediction in the short wave range, where forces due to wave reflection dominate, has been made applying semi-empirical corrections proposed by Kuroda. Experimental data for the heave, pitch, and added resistance of an ITTC benchmark KRISO container ship have been compared with numerical ones, and the applicability of the proposed method is discussed.

Key words: *Rankine panel method, vertical motions in waves, added resistance, KRISO container ship (KCS), Kuroda correction*

1. Introduction

A ship in waves is affected by a higher resistance than that in still water. The difference is known as added resistance, which is generated by energy dissipation due to ship motions and due to the reflection of incident waves. An accurate prediction of added resistance is therefore important for the evaluation of the increased power required to maintain the speed and in view of the related higher emissions and costs.

Several theoretical approaches of varying complexity and accuracy have been introduced in the past and numerically implemented/verified. The first far-field approach was introduced by Maruo [1, 2]. In the early 1970s, the radiated energy approach of Gerritsma and Beukelman [3] was introduced, which basically follows the far-field approach of Maruo. Strøm-Tejsen et al. [4] presented comparison of the above approaches and find large discrepancies between obtained results from different theoretical approaches and relevant model experimental data. Later on, in 1974, Salvesen [5] investigated the added resistance problem by applying Gerritsma's and Beukelman's method, but using the basic results of the so-called Salvesen, Tuck and Faltinsen (STF) seakeeping strip theory [6]. Salvesen got quite satisfactory results for the investigated ship hull forms due to the superiority of the STF strip theory method in the prediction of ship motions over other methods at that time. All those methods assume a slender ship and do not take into account wave diffraction, which is the main component of the added resistance for short waves. A near-field, direct pressure integration approach to the added resistance problem was introduced by Faltinsen et al. [7], with good validation results. The observed deficiency of the approach in short waves was addressed by the introduction of a simplified added resistance estimation formula, which describes well the complicated interaction between the diffraction of waves and the steady flow around the ship. The same problem occurs for full hull forms with blunt bows (bulk carriers and tankers), operating at low speed. More recently full 3D methods have become available for the application to the added resistance problem and a number of panel methods based on the near-field pressure integration have been developed. Arribas [8] applied three theories for the added resistance evaluation, i.e. the momentum and energy method (Joosen [9]), the integration pressure method (Salvesen [5]), and the radiated energy method, to three ship models. The basic potential and motions were evaluated by 2D strip theories. Computed results were compared with model tests in the towing tank and the range of application was commented on. Kim et al [10] extended a seakeeping analysis program, based on the time domain B-Spline Rankine panel method, to derive an added resistance formulation by the near-field approach. The program was validated by means of model tests, namely on a hemisphere and a barge for the zero speed problem, and on a Wigley hull, a C_B=0.60 Series 60 and a S175 container ship for the forward speed problem. Liu et al. [11] used three different methods to solve the basic seakeeping problem: frequency domain 3D panel method, new time domain Green function method and hybrid time domain Rankine source-Green function method. The added resistance was then evaluated by the Maruo-based far-field approach. As case tests, a submerged and floating spheroid, a Wigley hull, a Series 60 C_B=0.70 and a S175 container ship were considered. In Matulja et al. [12] a comparison between two methods, the Faltinsen and the Salvesen, for added resistance in regular waves was made for a bulk carrier, two container ships and a Ro-Ro ship. Both methods seem to predict the added resistance in head seas with similar accuracy in the region of longer waves, except for the bulk carrier, as it can be expected due to the full hull form. The authors highlighted that the typically used non-dimensional values of added resistance cannot illustrate their influence on the total resistance in terms of the total loss of speed or an increase in power, indicating that a percentage value, considering the ship resistance in still water, would be more significant.

Prpic-Orsic and Faltinsen [13] adopted the strip theory, direct integration pressure method, and the Faltinsen asymptotic formula to calculate the mean speed in heavy sea state when voluntary speed reduction occurs. The increase in CO_2 emission was evaluated as well. Joncquez et al. [14] presented new expressions for the second order forces and moments, using both the pressure integration and the momentum conservation methods. These expressions include both the influence of the flare angle and the second order geometrical interaction with the steady pressure. The obtained results are compared with experimental data for a Wigley hull, a Series 60 hull and a bulk carrier hull form, showing good agreement for all test cases. Seo et al [15] compared three different numerical methods for the determination of added resistance of ships in waves. The considered methods are: the strip method, the Rankine panel method, and the Cartesian grid method, which solves the Euler equation. In order to predict the added resistance, near- and far-field approaches are adopted in the strip and Rankine panel methods, while the Cartesian grid method is used to calculate the added resistance directly. The computational results are validated by comparing them with experimental data on Wigley hulls, Series 60 hulls, and the S175container ship, showing good agreement for all models.

This paper focuses on the methodology for the prediction of motions and added resistance by the three dimensional Rankine panel method as described in Bruzzone and Gualeni [16]. The semi-empirical procedure by Kuroda et al. [17] for the added resistance in short waves due to wave reflection at the bow is applied and its contributions have been added to ship motions. The obtained results are validated by comparing them with the experimental data from Joncquez et al. [14]. Comments on the applicability of the method are given.

2. Outline of the methodology

Ship motions are determined in the frequency domain in which the ship is considered advancing and oscillating. Only a brief outline relevant to the present paper is reported here.

The right-handed Cartesian reference system is considered. It advances at the vessel speed *U*, with the *x* axis coincident with the intersection of the symmetry plane of the ship and the undisturbed free surface and it is directed backward. The *z* axis is normal to the water plane and is positive upwards. The motions are defined as:

$$\eta_j = \varsigma_j e^{i\omega_e t}$$

where

ς_j for *j*=1,…,3 indicates the complex amplitude of the translations (surge, sway, heave) and for *j*=4,…,6 indicates the complex amplitude of rotations (roll, pitch, yaw).

The wave elevation at the origin of the steadily translating reference system is indicated as

$$\eta_0 = a e^{i\omega_e t}$$

To determine the hydrodynamic force, necessary to estimate ship motions, a set of three-dimensional boundary value problems has to be solved.

2.1 Boundary value problems

The water is supposed to be inviscid and incompressible, the flow irrotational, and the total potential Φ_T at a position $\vec{x} \equiv (x, y, z)$ is considered as:

$$\Phi_T(\vec{x},t) = \Phi_S(\vec{x}) + \left[\phi_0(\vec{x}) + \phi_7(\vec{x}) + \sum_{j=1}^{6} \phi_j(\vec{x})\varsigma_j\right] e^{i\omega_e t} \quad (1)$$

where:

$\Phi_S(\vec{x})$ is the steady potential due to uniform motion at the ship speed *U* and it is assumed as the free stream potential *Ux*,

$\phi_0(\vec{x})$ is the complex amplitude of the potential due to the incident waves,

$\phi_j(\vec{x})$ (*j*=1,…,6) are the complex amplitudes of the radiation potentials corresponding to each mode of motion of unitary amplitude

$\phi_7(\vec{x})$ is the complex amplitude of the diffraction potential.

Potentials $\phi_j(\vec{x})$ (*j*=1,…,7) are determined by solving a set of boundary value problems. They satisfy the Laplace equation in the fluid domain and the following boundary conditions.

The body conditions imposed on the mean hull surface S_H are:

for the radiation problems j=1,…,6:

$$\frac{\partial \phi_j}{\partial n} = i\omega_e n_j + m_j \tag{2}$$

for the diffraction problem:

$$\frac{\partial \phi_0}{\partial n} + \frac{\partial \phi_7}{\partial n} = 0 \tag{3}$$

where:

$$\begin{aligned}
&(n_1, n_2, n_3) = \vec{n} \\
&(n_4, n_5, n_6) = \vec{x} \times \vec{n} \\
&(m_1, m_2, m_3) = -\vec{n} \cdot \nabla(\nabla \Phi_S) \\
&(m_4, m_5, m_6) = -\vec{n} \cdot \nabla(\vec{x} \times \nabla \Phi_S).
\end{aligned}$$

For each problem (j=1,…,7) the linearized conditions imposed on the free surface S_F, assumed as $z = 0$, are:

$$\left[\frac{\partial^2}{\partial t^2} + g\frac{\partial}{\partial z} + 2\nabla\Phi_S \cdot \nabla\left(\frac{\partial}{\partial t}\right)\nabla\Phi_S \cdot \nabla(\nabla\Phi_S \cdot \nabla) + \frac{1}{2}\nabla(\Phi_S \cdot \Phi_S) \cdot \nabla\right]\phi_j = 0 \tag{4}$$

2.2 The numerical method

For the numerical solution of the foregoing boundary value problems, the potential ϕ_j at a point P and the gradient are considered as:

$$\phi_j(P) = \int_{S_H \cup S_F} \frac{1}{|\vec{x}_P - \vec{x}_Q|}\sigma(Q)dS \tag{5}$$

$$\nabla[\phi_j(P)] = \int_{S_H \cup S_F} \nabla\left[\frac{1}{|\vec{x}_P - \vec{x}_Q|}\right]\sigma(Q)dS \tag{6}$$

where

Q is the point on the boundary surfaces (S_H and S_F),

σ is the source density.

The mathematical model is discretised using N_T flat quadrilateral panels on the hull and on the free surface. The uniform source distribution of density σ_k (k=1,…,N_T) is applied to each of them. The boundary conditions lead to a system of NT linear algebraic equations in N_T unknown complex source strengths for each radiation and diffraction problem. The quadrilateral panels are obtained by dividing all the relevant boundary surfaces into patches or sections. On each section, two families of lines are used to form structured grids. The points of the grids are the panel vertices.

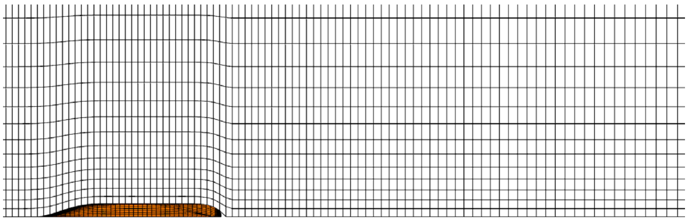

Fig. 1 Example of the panel representation of the boundary surface

Second order derivatives of the involved potentials on the free surface are computed through a backward finite difference operator in the longitudinal direction and an outward operator in the lateral direction. A proper radiation condition must be chosen at the foremost boundaries of each section of the free surface grid (shown in Figure 1).

When all potentials have been determined, pressures on the hull derived from each of the potentials are calculated as well as the added mass, damping matrices and exciting forces. Finally, the ship motions $[\eta]$ are obtained by solving an equation of motion given as:

$$\left[M + A\right][\ddot{\eta}] + \left[B\right][\dot{\eta}] + \left[C\right][\eta] = [F_{FK}] + [F_{HD}] \tag{7}$$

where:

$[M]$ - is the mass matrix of the ship,

$[A]$ - is the added mass matrix,

$[B]$ - is the damping matrix,

$[C]$ - is the restoring term matrix,

$[F_{FK}]$ – is the Froude-Krilov force vector,

$[F_{HD}]$ – is the hydrodynamic force vector.

2.3 Formulation for the added resistance calculation

The added resistance of a ship in regular waves results from ship motions in regular waves and from the wave reflection.

For the prediction of added resistance, the far-field method is generally used due to a more straightforward application. With the relevant development of computer power, the near-field method has become widely used. In the present study, the near-field method based on the frequency domain approach is derived. By considering Bernoulli's equation and the perturbation expansion for the motions and pressures, the second-order pressure can be estimated and the second-order force is obtained by integrating the second-order pressure on the body surface. It can be shown that non null time averaged values are obtained by cross multiplying first order effects and by considering first order variations of the mean hull surface. Thus, it is not necessary to solve the second-order boundary value problem.

The added resistance due to ship motions may be divided into two principal terms: R_{AW1} and R_{AW2}. The term R_{AW1} derives from the difference between the average and the instantaneous wetted surface and it is given by the following relation:

$$R_{AW1} = \overline{\int_{WL} \frac{1}{2} \rho g \zeta_r \, dl} \tag{8}$$

where

WL is the waterline contour,

ζ_r is the first-order difference between the average (steady) and the instantaneous wave profile on the hull given by:

$$\varsigma_r = \sum_j \varsigma_j(l) - \varsigma_3(l) \tag{9}$$

where

$\zeta_j(l)$ is the wave elevation relative to the various boundary value problems,

$\zeta_3(l)$ is the vertical displacement at a point on the waterline.

The second contribution, R_{AW2}, to the added resistance is the pressure integral over the average wetted surface where only the second-order terms of the integrand are retained:

$$\begin{aligned} R_{AW2} &= \rho \overline{\int_{S_H} \frac{1}{2} \nabla\phi^{1st} \cdot \nabla\phi^{1st} n_1 dS} \\ &+ \rho \overline{\int_{S_H} \nabla\left[\frac{\partial\phi^{1st}}{\partial t} + \left(\nabla\Phi_S \nabla\phi^{1st}\right)\zeta_P\right] n_1 dS} \\ &+ \rho \overline{\int_{S_H} \nabla\left[\frac{\partial\phi^{1st}}{\partial t} + \nabla\Phi_S \nabla\phi^{1st} + g\zeta_P\right] n_1 dS} \end{aligned} \tag{10}$$

where

ζ_P is the vector which expresses the motion at a point P on the hull surface,

ϕ^{1st} is the sum of 1st order potentials relevant to the sum of each radiation and diffraction problem.

The added resistance due to the reflection in short waves R_{AW-SW}, where short waves are defined with $\lambda<0.5L$, may be evaluated by the empirical formula (11)

$$R_{AW-SW} = \frac{1}{2}\rho g \varsigma_a B_{WL} B_f \alpha_d \left(1+\alpha_u\right) \tag{11}$$

where

ζ_a – is the amplitude of regular waves,

B_{WL} – is the ship breadth at waterline,

α_d – is the coefficient to account for the effect of draft and wave frequency,

B_f – is the bluntness coefficient,

α_U – is the effect of advance speed.

Coefficient α_d has been derived as a theoretical formula for the wall sided hull by Fujii and Takahashi in 1975 [18] and by Kuroda in 2008 [17] to better fit experimental data. The expression for α_d (12) used in this method is the one by Kuroda, where a wave number based on the encounter frequency k_e is proposed instead of the wave number.

$$\alpha_d\left(k_e T\right) = \frac{\pi^2 I_1^2\left(k_e T\right)}{\pi^2 I_1^2\left(k_e T\right) + K_1^2\left(k_e T\right)} \tag{12}$$

where

I_1 is the modified Bessel function of the first kind of order 1,

K_1 is the modified Bessel function of the second kind of order 1,

$k_e=\omega_e^2/g$,

T is the draft.

Bluntness coefficient is defined as:

$$B_f = \frac{1}{B}\left[\int_I \sin^2(\alpha + \beta_w)\sin\beta_w dl + \int_{II} \sin^2(\alpha - \beta_w)\sin\beta_w dl\right] \tag{13}$$

where *I* and *II* are non-shaded parts of the waterline in front of the oncoming wave, *I* is on the ship side directly exposed, *II* is on the symmetric side (see Fig. 2), *dl* is the line element, β_w is the slope of line element, α is the angle the wave direction forms with the negative *x* axis.

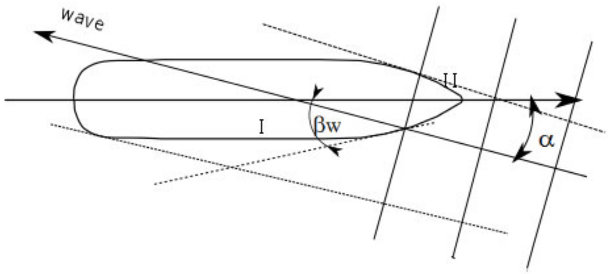

Fig. 2 Definition of terms in the bluntness coefficient (adapted from Kuroda et al.,[17])

The effect of the advance speed is calculated as:

$$1 + \alpha_U = 1 + C_U Fr \tag{14}$$

$$C_U = \max\left[10.0, -310B_f + 68\right] \tag{15}$$

Finally, the total resistance increment of a ship in waves $R_{AW\text{-}TOT}$ can be evaluated approximately as the sum of the resistance enhancement due to ship motions and the component due to wave reflection at the bow.

$$R_{AW-TOT} = R_{AW} + R_{AW-SW} \tag{16}$$

3. Application and discussion

The application considered is related to a KRISO Container Ship (KCS), one of the ITTC benchmark models, reported in Guo [19] and ITTC [20], shown in Fig.3. The main characteristics of the vessel are given in Table 1.

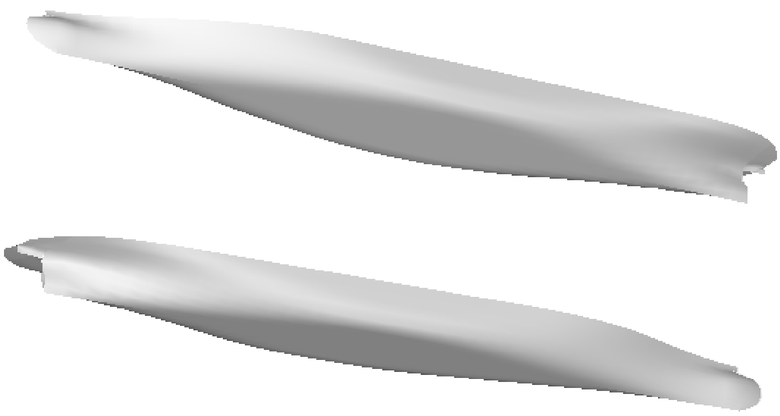

Fig. 3 KRISO Container ship

Table 1 Principal characteristics of KRISO container ship

Principal characteristics		SI Unit
L_{PP}	230.00	m
L_{OA}	232.5	m
B_{WL}	32.20	m
T	10.80	m
C_B	0.6505	-
V	52030	m^3
r_{55}	$0.22L_{PP}$	m
VCG	10.80	M

Numerical results are compared with experimental data taken from Joncquez [14]. Calculations of the heave and pitch motions and of added resistance are performed for the Froude number Fr=0.26. Heave and pitch transfer functions (RAO) are defined as the first order response amplitude divided by the first order wave amplitude, as in (17):

$$RAO_3 = \frac{|\varsigma_3|}{a} \qquad RAO_5 = \frac{|\varsigma_5|}{k \cdot a} \tag{17}$$

The mean added resistance coefficient σ_{AW} is defined in eq. (18)

$$\sigma_{AW} = \frac{R_{AW-TOT}}{\rho g a^2 B_{WL}^2 / L_{PP}} \tag{18}$$

where

$R_{AW\text{-}TOT}$ is the total added resistance of the ship,

B_{WL} and L_{PP} are the hull breadth at waterline and the length between perpendiculars, respectively,

a is the incident wave amplitude,

ρ is the fluid density,

g is the gravity acceleration.

Results are plotted as a function of the wave length divided by the ship length.

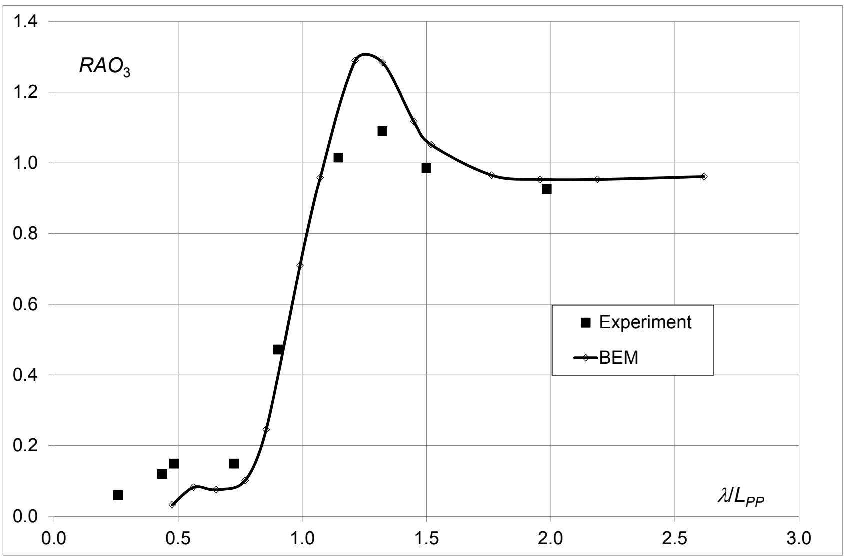

Fig. 4 Comparison between the experimental and the numerical heave RAO

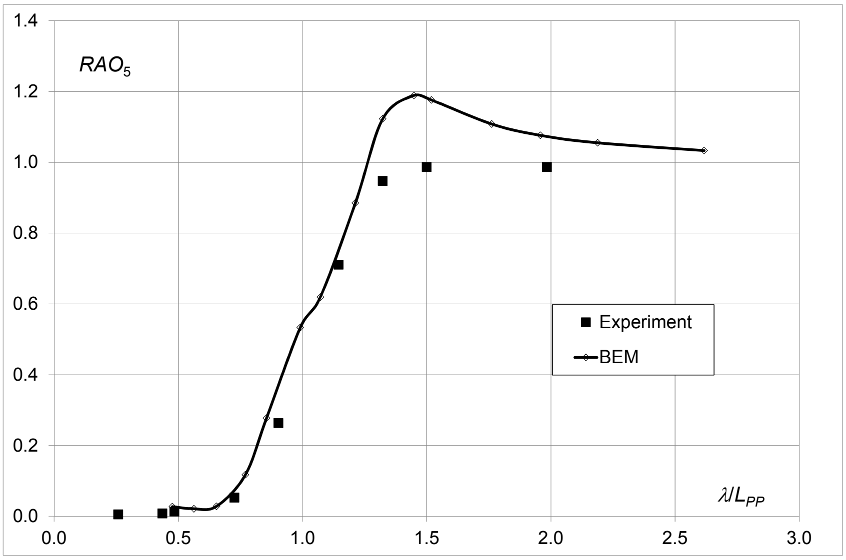

Fig. 5 Comparison between the experimental and the numerical pitch RAO

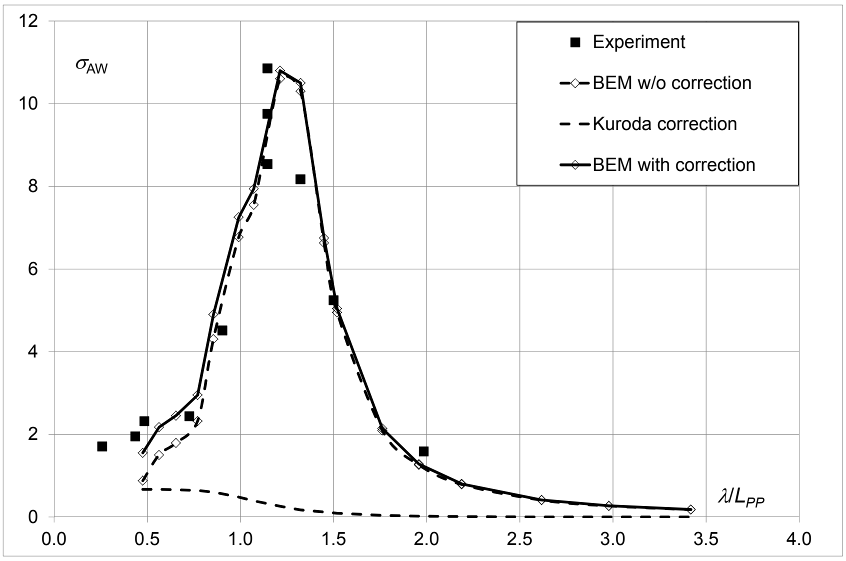

Fig. 6 Comparison between the experimental and the numerical mean added resistance

From Figs. 4 and 5 one can note that the heave and pitch motions are overestimated in the resonance frequency. This effect is commonly brought about by the underestimation of the damping term. This behaviour has an impact on the assessment of the added resistance. In fact, some overestimation can be observed in Fig. 6 in the prediction of the added resistance peak value. In addition, it can be noted that in the range of long wave lengths, the correspondence with experimental data is good, while in the range of small wave lengths, the results without correction for short waves are underestimated. Applying the formulation proposed by Kuroda [17] for the added resistance due to reflection, the obtained numerical results fit better the experimental ones. The range of wave frequencies where the correction is effective can be identified: it gives a remarkable improvement up to λ/L_{PP} of approximately 1.

4. Conclusions and future work

In this paper, a methodology for the prediction of ship motions and added resistance in waves is presented. It is based on the three dimensional panel method approach developed in the frequency domain. The added resistance issue is dealt with by exploiting the near-field approach.

Added resistance is obtained as a second-order force by integrating the second-order pressure on the body surface.

Due to the inherent shortcoming of the adopted methodology, a semi-empirical procedure for capturing the added resistance component in short waves is applied. The methodology has been validated for a container ship KRISO (KCS), ITTC benchmark, using experimental data available in the literature.

The Rankine panel method, based on the potential theory, overestimates the resonance values of vertical motions and this has a great influence on the added resistance component due to ship motions, leading to overestimation of the total added resistance in resonance.

It could be said that although for a modern container ship with fine forms, the part of wave reflection due to advance speed is higher than that due to the bluntness coefficient, the added resistance due to reflection in short waves, calculated by the Kuroda correction [17], has provided satisfactory results and has proven to be a valuable tool for improving the added resistance prediction for this type of ships.

Research on added resistance will continue with the validation of the foregoing numerical method with new experimental data. The added resistance due to reflection in shorter waves, for which the Kuroda correction was applied, will be investigated for geometries characterized by a blunt bow, like tanker hull forms, for very short wave lengths where this component is expected to have a marked effect.

NOMENCLATURE

a – wave amplitude, m

$[A]$ - added mass matrix, kg, kgm^2

B_{WL} – beam at waterline, m

$[B]$ - damping matrix, kg/s, kgm^2/s

$[C]$ - restoring matrix, kg/s^2, kgm^2/s^2

F_{FK} – Froude Krilov force, N

F_{HD} – hydrodynamic force, N

Fr –Froude number based on waterline length $Fr = \frac{v}{\sqrt{g \cdot L}}$

g – acceleration of gravity, 9.80665 m/s^2

k – wave number, rad/m

k_e – wave number based on the encounter frequency, rad/m

L_{OA} – length over all, m

L_{PP} – length between perpendiculars, m

LCG – longitudinal position of the centre of gravity from transom, m

R_{AW} – added resistance in waves, N
$R_{AW\text{-}SW}$ – added resistance in waves due to the reflection in short waves, N
$R_{AW\text{-}TOT}$ – total added resistance in waves, N
r_{55} – pitch radii of gyration, m
T – draught, m
v – speed, m/s
∇ – displacement volume, m^3
VCG – vertical position of the centre of gravity, m
Δ – displacement, N
λ – wave length, m
λ/L – ratio wave length over ship length
η_3 – heave displacement, m
η_5 – pitch displacement, deg
ω – wave frequency, rad/s
ω_e – encounter frequency, rad/s

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