A comparison of methods for computing the added resistance of ships using a high-order BEM

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The validation of added resistance is of importance for both commercial and navy ships since it affects both economical performance and range. In order to provide guidance to the designer at an early stage, it is important to have a reliable computational tool. One such tool is AEGIR. Full details of AEGIR can be found in [3]. AEGIR is a time domain, three-dimensional, high-order Boundary Element Method (BEM). In this abstract, we will present the theory for predicting added resistance using both Neumann-Kelvin and double-body flow linearizations. Both near-field and far-field approaches are considered. Results are compared with experimental data for three hull forms. The aim of this work is to determine which linearization and method is most reliable for general ship hulls.

Consider a floating body at steady forward speed. Two reference frames are employed: the earth-fixed inertial frame (X_0, Y_0, Z_0); and the ship-fixed frame (x, y, z) which follows the steady motion of the ship. The ship-fixed reference frame translates with the ship's mean forward speed U, and mean side-slip speed V, and rotation about the Z_0 axis with mean angular velocity Ω. The surfaces S_F and S_B represent respectively the instantaneous submerged hull surface and the free surface, as shown in Figure 1. The mean velocity $\vec{W}$ is defined as : $\vec{W} = (U - \Omega y)\vec{i} + (U + \Omega x)\vec{j}$, where $\vec{i}$ and $\vec{j}$ represent the unit vectors along the x- and y-axis respectively.
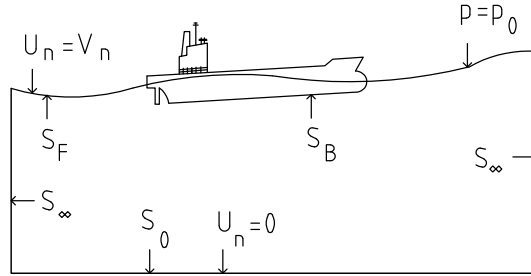

Figure 1: Control volume

The Boundary Value Problem is expressed with respect to the reference frame $\vec{x}$. The generalized normal vector is N_i, $i = 1, 6$; with $i = 1, 3$ representing the normal vector components in the X_0, Y_0 and Z_0 directions, and $i = 4, 6$ representing the vector $\vec{N} \cdot \vec{X}$

The instantaneous forces can be expressed via integration of pressure as:

$$F_i = \int_{S_B} P N_i ds \qquad \text{with } i = 1, 6 \qquad (1)$$

with $i = 1, 3$ representing the forces and $i = 4, 6$ the moments.

Two approaches are considered to calculate the mean second order forces and moments: the pressure integration method (near-field approach) and the momentum conservation method (far-field approach). The total potential is linearized up to order 2 with respect to the sum of the free stream and the steady base flow Φ.

$$\Psi = \Phi + \phi^{(1)} + \phi^{(2)} \qquad (2)$$

The wave elevation ζ and the pressure p are also expanded up to second order:

$$\zeta = \zeta^{(0)} + \zeta^{(1)} + \zeta^{(2)} \qquad P = P^{(0)} + P^{(1)} + P^{(2)}. \tag{3}$$

We consider here both the Neumann-Kelvin linearization ($\Phi = 0$) and the double-body flow linearization ($\partial \Phi / \partial z = 0$ on $z = 0$).

We write $\vec{\xi_T} = (\xi_1, \xi_3, \xi_3)$ and $\vec{\xi_R} = (\xi_4, \xi_5, \xi_6)$ the generalized motions. In the near-field approach, the earth-fixed quantities must be expressed in terms of the ship-fixed quantities:

$$\vec{X} = \vec{x} + \vec{\xi_T} + \vec{\xi_R} \times \vec{x} + H\vec{x} \tag{4}$$

$$\vec{N} = \vec{n} + \vec{\xi_T} + \vec{\xi_R} \times \vec{n} + H\vec{n} \tag{5}$$

$$P\left(\vec{X}\right) = -\rho \left[g\left(z - Z_0\right) + \phi_t(\vec{x}) - \vec{W} \cdot \nabla \phi(\vec{x}) + g\left(\xi_3 + \xi_4 y - \xi_5 x\right) \right] \tag{6}$$

$$- \rho \left[\frac{1}{2} \nabla \phi \cdot \nabla \phi + \left(\vec{\xi_T} + \vec{\xi_R} \times \vec{x}\right) \cdot \nabla \left(\phi_t(\vec{x}) - \vec{W} \cdot \nabla \phi(\vec{x})\right) + gH\vec{x} \cdot \nabla z \right].$$

Here the matrix H is a transformation matrix defined by

$$H = \frac{1}{2} \begin{pmatrix} -(\xi_5^2 + \xi_6^2) & 0 & 0 \\ 2\xi_4 \xi_5 & -(\xi_4^2 + \xi_6^2) & 0 \\ 2\xi_4 \xi_6 & 2\xi_5 \xi_6 & -(\xi_4^2 + \xi_5^2) \end{pmatrix} \tag{7}$$

The instantaneous wetted surface can be divided into two surfaces:

1. The mean wetted surface in calm water.

2. The surface coming from the heaving, pitching, and rolling of the ship and from the wave elevation.

The flare angle α is defined such that $\alpha = \pi/2$ for vertical wall side. Assuming that the motions and the wave amplitude are small, and that the flare angle α is independant of z, the second order generalized force is expressed as:

$$F_i = \iint_{S_{\bar{B}}} P N_i ds + \int_{WL} \int_{\xi_3 + y\xi_4 - x\xi_5}^{\zeta} P \frac{N_i}{\sin \alpha} dz dl \tag{8}$$

where ξ_3, ξ_4 and ξ_5 are the heave, roll, and pitch amplitudes. The first integral corresponds to the integral of the second order pressure over the mean body position (it will be called $\vec{F}_{mb}$), and the second integral corresponds to the integral of the first order pressure around the waterline (it will be called $\vec{F}_{wl}$). Using equations 4, 6 and 7, these contributions become

$$\vec{F}_{mb} = -\rho \left[\iint_{S_{\bar{B}}} \vec{n} \left(\frac{1}{2} \nabla \phi \cdot \nabla \phi + \left(\vec{\xi_T} + \vec{\xi_R} \times \vec{n}\right) \cdot \nabla \left(\phi_t(\vec{x}) - \vec{W} \cdot \nabla \phi\right) + gH\vec{x} \cdot \nabla z \right) ds \right] \tag{9}$$

$$- \rho \left[\iint_{S_{\bar{B}}} \left(\vec{\xi_R} \times \vec{n}\right) \left(\phi_t(\vec{x}) - \vec{W} \cdot \nabla \phi(\vec{x}) + g\left(\xi_3 + \xi_4 y - \xi_5 x\right)\right) ds \right]$$

$$- \rho \left[\iint_{S_{\bar{B}}} H\vec{n} g\left(z - Z_0\right) ds \right]$$

and

$$\vec{F}_{wl} = \frac{1}{2} \rho g \int_{WL} \zeta \left[\zeta - 2\left(\xi_3 - y\xi_4 + x\xi_5\right)\right] \vec{n}^0 dl \tag{10}$$

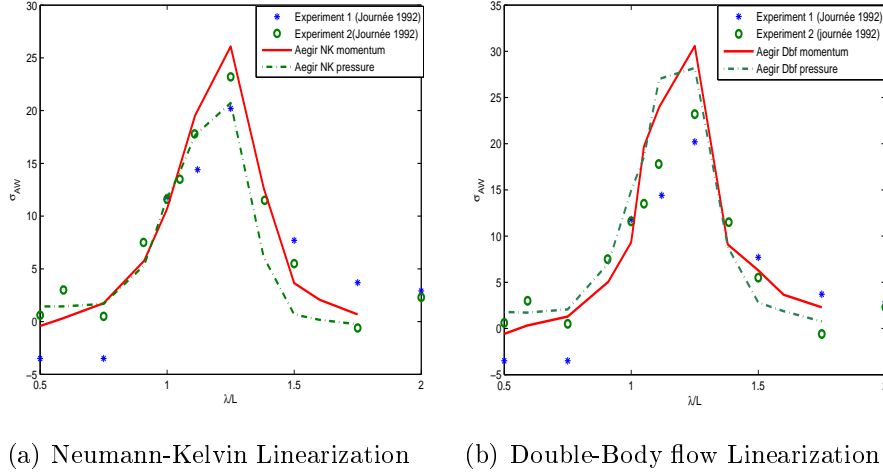(a) Neumann-Kelvin Linearization (b) Double-Body flow Linearization

Figure 2: Added Resistance for the Wigley hull III

where $\vec{n}^0$ is the normal vector to the body surface in it's mean position.

The other method that can be used is the momentum conservation method. Applying momentum conservation to the fluid volume Ω defined in Figure 1 (where S_∞ is usually a cylinder), we obtain an expression for the mean second-order force $\vec{F}$. This result is only valid for the x- and y- directions.

$$\overline{\vec{F}} = \overline{\rho \iint_{S_B} \frac{p}{\rho} \vec{n} ds} = -\overline{\rho \iint_{S_\infty} \left[\frac{p}{\rho} \vec{n} + \vec{V} V_n \right] ds} \tag{11}$$

The surface S_∞ can be divided into two surfaces: S_d which represents the part of S_∞ lying below z=0, and the surface coming from the wave elevation. C_d represents the intersection of S_∞ with the z=0 plane.

$$\overline{\vec{F}} = \overline{-\rho \iint_{S_d} \left[\frac{p}{\rho} \vec{n} + \vec{V} V_n \right] ds} = \overline{-\rho \int_{C_d} \int_{z=0}^{\zeta} \left[\frac{p}{\rho} \vec{n} + \vec{V} V_n \right] ds} \tag{12}$$

Equations 9, 10 and 12 can be applied using either the Neumann-Kelvin or the double-body linearization. These two methods have been tested for three different ships: the Wigley hull III [2], the Series 60 [4] and a bulk carrier. Calculations of the added-resistance coefficient σ_{AW} have been made over a range of incident wavelengths λ, and dimensionless frequency of encounter μ_e. Figure 2 shows the calculations for the Wigley hull III at Froude number $Fn = 0.3$ compared with experimental measurements.

Figures 3 and 4 show the results using the Series 60 hull at $Fn = 0.222$ and a tanker hull at $Fn = 0.166$. The tanker model experiments were done by Force Technology, Denmark and were obtained by personal communication but are unfortunately not publicly available. It has been necessary to simplify the hull for the tanker in order to make the double-body flow linearization converge with the pressure integration method.

Given the relatively large experimental uncertainties involved in measuring added-resistance, reasonably robust and consistent results are obtained using both near- and far-field methods together with either Neumann-Kelvin or double-body linearizations for all three hulls.
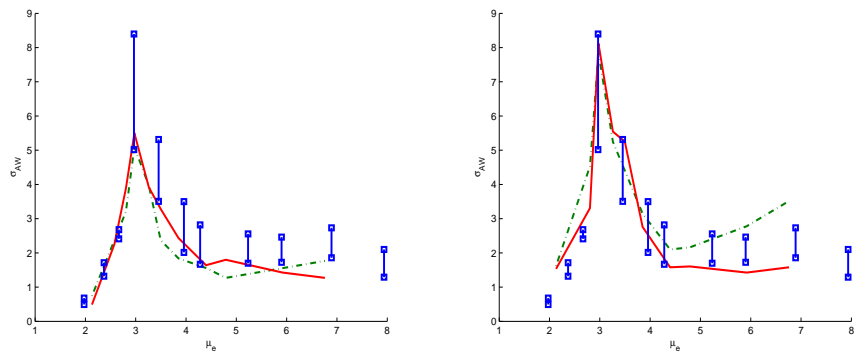
References

[1] Joncquez,S. A. G., Bingham, H., Andersen, P. and Kring, D. C.,**Validation of Added Resistance Computations by a Potential-Flow Boundary-Element Method**, 27th *Symposium on Naval Hydrodynamics*, 5-10 October 2008
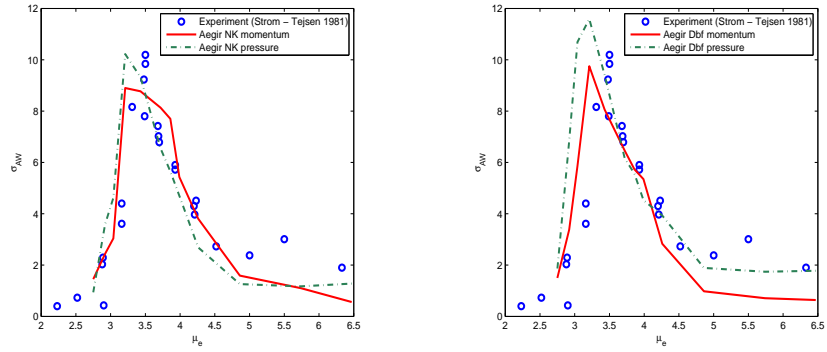
(a) Neumann-Kelvin Linearization   (b) Double-Body flow Linearization

Figure 3: Added Resistance for the Series 60

(a) Neumann-Kelvin Linearization   (b) Double-Body flow Linearization

Figure 4: Added Resistance for the tanker; Red line: AEGIR with momentum conservation. Green dashed line: AEGIR with pressure integration method. Blue lines: experimental data.

[2] Journée, J. M. J.,**Experiments and Calculations on Four Wigley Hull Forms in Head Waves**,0909, May 1992, Delft Universoty of Technology

[3] Kring, D. C., Milewski, W. M. and Fine, N. E.,**Validation of a NURBS-Based BEM for Multihull Ship Seakeeping**, 25th *Symposium on Naval Hydrodynamics*, 8-13 August 2004

[4] Strom-Tejsen, J., Yeh, H. Y. H. and Moran, D. D.,**Added Resistance in Waves**, *Transaction of SNAME*, 1981, pp. 109-143