Comparative Study on Added Resistance Computation

Min-Guk Seo, Dong-Min Park, Jae-Hoon Lee, Kyong-Hwan Kim, Yonghwan Kim

Seoul National University
Introduction

• Research Background
  - In recent years, discussions at the International Maritime Organization (IMO) have resulted in the development of an Energy Efficiency Design Index (EEDI) to restrict greenhouse gas emissions from ships.

http://www.theicct.org/blogs/staff/cutting-carbon-ships
Introduction

- Research Background

  - The design of ships with less green-house gas is of great interest in naval architecture fields. Ship designers need to find optimum hull forms to minimize the resistance including the added resistance in waves.

  - When a ship navigates in waves, the ship’s forward speed decreases compared to that in calm sea because of the added resistance.

→ An accurate computation of added resistance is getting more important for the prediction of power increase on ships in random ocean waves.
Methodology

Strip Method
Rankine Panel Method
CFD method
Experiment

Motion RAOs

Near-field Method
Far-field Method

Force Analysis

Added Resistance

Total force in waves
Mean value of total force in waves
Steady force in calm water
State of the Art

• Far-field Method
  - Maruo (1960) : Propose far-field method
  - Gerritsma & Beuklman (1972), Salvesen (1978) : Radiated energy method
  - Joncquez et al. (2008) : Rankine panel method in time domain
  - Kashiwagi et al. (2009) : Enhanced Unified Theory (EUT) + correction in short waves

• Near-field Method
  - Faltinsen et al. (1980) : Strip method, asymptotic approach in short waves
  - Joncquez et al. (2008) : Rankine panel method in time domain
  - Kim & Kim (2011) : Rankine panel method in time domain, direct simulation in irregular waves

• Added Resistance in Short Waves
  - Fujii & Takahashi (1975) : Drift force on cylinder + correction coefficient for ship shape, speed
  - Faltinsen et al. (1980) : Asymptotic approach in short wave
  - Kuroda et al. (2008) : Fujii & Takahashi method + correction
In the Present Study

• A frequency-domain strip method and a time-domain Rankine panel method are applied to calculate the first-order potential and linear ship responses, as a necessity for the added resistance calculation.

• Both the near-field method (direct pressure integration method) and far-field method (momentum conservation method, radiated energy method) are adopted for the calculation of added resistance.

• The established asymptotic approaches are examined to evaluate added resistance in short wavelength.
Boundary Value Problem (Rankine Panel Method)

- Equation of Motion
  
  \[ (\ddot{\xi} = \ddot{\zeta} + \dot{\zeta} \times \ddot{\mathbf{x}}) \]

  \[ [M_{jk}] \{\ddot{\xi}_k\} = \{F_{H.D.,j}\} + \{F_{F.K.,j}\} + \{F_{Res.,j}\} \]

  \[ (k, j = 1, 2, \ldots, 6) \]

  - \( F_{Res} \): Restoring force
  - \( F_{F.K.} \): Froude-Krylov force
  - \( F_{H.D.} \): Hydrodynamic force

- Linearized Boundary Value Problem

  - Governing Equation
    \[ \nabla^2 \phi = 0 \quad \text{in fluid domain} \]

  - Body B.C.
    \[ \frac{\partial \phi_d}{\partial n} = \sum_{j=1}^{6} \left( \frac{\partial \zeta_j}{\partial t} n_j + \zeta_j m_j \right) - \frac{\partial \phi_t}{\partial n} \quad \text{on } S_B \]

    \[ (m_1, m_2, m_3) = (\bar{n} \cdot \nabla)(\bar{U} - \nabla \Phi) \]

    \[ (m_4, m_5, m_6) = (\bar{n} \cdot \nabla)(\bar{x} \times (\bar{U} - \nabla \Phi)) \]

  - Kinematic F.S.B.C.
    \[ \frac{\partial \zeta_d}{\partial t} - (\bar{U} - \nabla \Phi) \cdot \nabla \zeta_d = \frac{\partial^2 \Phi}{\partial z^2} \zeta_d + \frac{\partial \phi_d}{\partial z} + (\bar{U} - \nabla \Phi) \cdot \nabla \zeta_t \quad \text{on } z = 0 \]

  - Dynamic F.S.B.C.
    \[ \frac{\partial \phi_d}{\partial t} - (\bar{U} - \nabla \Phi) \cdot \nabla \phi_d = -\frac{\partial \Phi}{\partial t} - g \zeta_d + \left[ \bar{U} \cdot \nabla \Phi - \frac{1}{2} \nabla \Phi \cdot \nabla \Phi \right] + (\bar{U} - \nabla \Phi) \cdot \nabla \phi_t \quad \text{on } z = 0 \]
Added Resistance (Rankine Panel Method)

- **Near-field Method, Direct Pressure Integration Method (Kim & Kim, 2011)**

\[
\vec{F}_2 = \int_{\partial C_1} \left[ \frac{1}{2} \rho g \left( \zeta - (\xi_{1} + \xi_{2} y - \xi_{3} x) \right)^2 \cdot \hat{n}_1 dL - \rho \int_{\partial C_1} \left( -U \frac{\partial \Phi}{\partial x} + \frac{1}{2} \nabla \Phi \cdot \nabla \Phi \right) \left( \zeta - (\xi_{1} + \xi_{2} y - \xi_{3} x) \right) \cdot \hat{n}_1 dL \right] - \rho \int_{\partial C_1} \left( -U \frac{\partial \Phi}{\partial x} + \frac{1}{2} \nabla \Phi \cdot \nabla \Phi \right) \left( \zeta - (\xi_{1} + \xi_{2} y - \xi_{3} x) \right) \cdot \hat{n}_1 dL
\]

- **Far-field Method, Momentum Conservation Method (Joncquez, 2009)**

\[
\vec{F}_2 = \int_{C_1} \frac{\left[ \nabla (\phi_1 + \phi_3) \cdot \nabla (\phi_1 + \phi_3) + k^2 (\phi_1 + \phi_3)^2 \right]}{2k} \hat{n}_1 dL
\]

\[
- \rho \int_{C_1} \frac{\nabla (\phi_1 + \phi_3) \cdot \nabla (\phi_1 + \phi_3) \cdot \hat{n}_1}{2k} dL
\]

\[
+ \frac{\rho g}{2} \int_{C_1} \zeta^2 \hat{n}_1 dL + \rho \int_{C_1} \left[ \frac{\partial (\phi_1 + \phi_3)}{\partial t} - (\nabla \Phi) \cdot \nabla (\phi_1 + \phi_3) \right] \zeta \hat{n}_1 dL
\]

\[
- \rho \int_{C_1} \nabla \Phi (\nabla (\phi_1 + \phi_3) \cdot \hat{n}_1) + \nabla (\phi_1 + \phi_3) (\nabla \Phi \cdot \hat{n}_1) \zeta dL
\]

\[C_d: \text{Intersection of the control surface with } z = 0 \text{ plan} \]

\[n_c: \text{Normal vector of the control surface} \]

\[\zeta: \text{Wave elevation} \]
Strip Method

- Boundary Value Problem (2D)
  - 2D Wave Green function.
  - Governing equation \( \nabla^2 \phi = 0 \) in fluid domain
  - Free surface B.C. \( \frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \) on \( z = 0 \)
  - Body B.C. \( \frac{\partial \phi}{\partial n} = V_n \) on \( S_B \)

- Equation of Motion

\[
\sum_{k=1}^{6} \left[ \left( M_{jk} + A_{jk} \right) \ddot{\xi}_k + B_{jk} \dot{\xi}_k + C_{jk} \xi_k \right] = F_j e^{i\omega t}
\]

- \( A_{jk} \): Added mass
- \( B_{jk} \): Damping coefficient
- \( F_j \): Excitation force
Added Resistance (Strip Method)

- **Near-field Method, Direct Pressure Integration Method** (Faltinsen et al., 1980)

\[
F_{2,x} = \int_{S_a} \left( -\frac{\rho g}{2} \frac{\xi_r^2}{\zeta_r^2} \right) n_z ds - w_c^2 M_1 \xi_2 \xi_3 + w_c^2 M_2 (\xi_2 - z_g \xi_4) \xi_6 \\
+ \rho \int_{S_a} \left( (\xi_2 + x \xi_6 - z \xi_4) \frac{\partial \phi^{(1)}}{\partial y} + U \frac{\partial \phi^{(1)}}{\partial x} \right) \left( (\xi_3 - x \xi_5 + y \xi_4) \frac{\partial \phi^{(1)}}{\partial z} + U \frac{\partial \phi^{(1)}}{\partial x} \right) ds
\]

- **Far-field Method 1, Momentum Conservation Method** (Maruo, 1960)

\[
F_{2,x} = \frac{\rho k^2}{8\pi} \int_0^{2\pi} |H(\theta)|^2 (\cos \theta + \cos \beta) d\theta \\
H(\theta) = \int_{S_a} \left[ -o B(x) \left\{ A e^{-i k x \cos \beta} + i \xi - i x \xi \right\} \right] e^{-i k x \cos \theta} ds
\]

- **Far-field Method 2, Radiated Energy Method** (Salvensen, 1978)

\[
F_{2,x} = -\frac{i}{2} k \cos \beta \sum_{j=3,5} \xi_j \left\{ (F_j^*) + \hat{F}_j \right\} + R_7 \\
R_7 = -\frac{1}{2} \xi_1^2 \frac{\omega^2}{\omega_e^2} k \cos \beta \int_L e^{-2kd} (b_{33} + b_{22} \sin^2 \beta) dx
\]
Added Resistance in Short Waves

- Faltinsen et al. (1980)

\[ \overline{F}_2 = \int L \overline{F}_n \tilde{n}dL \]
\[ \overline{F}_n = \frac{1}{2} \rho g \zeta_f^2 \sin^2(\theta - \beta) + \frac{2\omega U}{g} \left[ 1 + \cos \theta \cos(\theta - \beta) \right] \]
\[ n_1 = \sin \theta \]
\[ n_2 = \cos \theta \]
\[ n_6 = x_0 \cos \theta - y_0 \sin \theta \]

- Fujii & Takahashi (1975), Kuroda et al. (2008)

\[ \overline{F}_2 = \alpha_d (1 + \alpha_u) \left[ \frac{1}{2} \rho g \zeta_f^2 B B_f(\beta) \right] \]
\[ B_f(\beta) = \frac{1}{B} \left[ \int_i \sin^2(\theta - \beta) \sin \theta dl + \int_{ii} \sin^2(\theta + \beta) \sin \theta dl \right] \]

Fujii & Takahashi (1975) \quad Kuroda et al. (2008)
\[ \alpha_d = \frac{\pi^2 I_1^2(kd)}{\pi^2 I_1^2(kd) + K_1^2(kd)} \]
\[ \alpha_d = \frac{\pi^2 I_1^2(kd)}{\pi^2 I_1^2(kd) + K_1^2(kd)} \]
\[ 1 + \alpha_u = 1 + 5\sqrt{F_n} \]
\[ 1 + \alpha_u = 1 + C_u F_n, \quad C_u = \max[10.0, -310B_f(\beta) + 68] \]
# Test Models

**Principle Particulars and Examples of Panel Model**

<table>
<thead>
<tr>
<th>Model</th>
<th>Wigley I</th>
<th>Wigley III</th>
<th>Series 60 $C_B = 0.7$</th>
<th>Series 60 $C_B = 0.8$</th>
<th>S-175</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>100 m</td>
<td>100 m</td>
<td>100 m</td>
<td>121.92 m</td>
<td>175 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>10 m</td>
<td>10 m</td>
<td>14.28 m</td>
<td>18.76 m</td>
<td>25.4 m</td>
</tr>
<tr>
<td>Draft</td>
<td>6.25 m</td>
<td>6.25 m</td>
<td>5.7 m</td>
<td>7.5 m</td>
<td>9.5 m</td>
</tr>
<tr>
<td>Volume</td>
<td>3503.7 m$^3$</td>
<td>2888.9 m$^3$</td>
<td>5624.5 m$^3$</td>
<td>13723.3 m$^3$</td>
<td>24135.5 m$^3$</td>
</tr>
<tr>
<td>Center of gravity</td>
<td>5.67 m</td>
<td>5.67 m</td>
<td>5.7 m</td>
<td>6.645 m</td>
<td>8.5 m</td>
</tr>
</tbody>
</table>
Simulation Results (Rankine Panel Method)

- Wave Contours

(a) Total wave contour
(b) Disturbed wave contour

- S-175 containership, $F_n = 0.15$, $\lambda/L = 0.7$
Comparison of Motion Response

(a) Heave motion
- Wigley I model, $F_n = 0.2$
- Wigley II model, $F_n = 0.3$
- Wigley II model, $F_n = 0.2$

(b) Pitch motion
- Wigley I model, $F_n = 0.2$
- Wigley II model, $F_n = 0.3$

Experiment (Journé, 1992)
Rankine panel method
Strip method
Convergence Test

- Convergence Test for Control Surface (Momentum Conservation Method + RPM)

Examples of control surface

Control surface is placed farther than $d_{CS}/\lambda = 3.0$

Wigley III model: $F_n = 0.2$, $\lambda/L = 0.9$
Time signals (Rankine Panel Method)

- Time-Histories of Surge Force

(a) Direct pressure integration method

(b) Momentum conservation method

- Wigley III model, $F_n = 0.2$, $\lambda/L = 1.0$
Results of Added Resistance (Wigley I model)

(a) Rankine panel method

(b) Strip method
- Wigley I model, Fn = 0.2
- Wigley I model, Fn = 0.3
Results of Added Resistance (Wigley III model)

- **(a) Rankine panel method**
  - Experiment (Journée, 1992)
  - Direct Pressure Integration Method + RPM
  - Momentum Conservation Method + RPM

- **(b) Strip method**
  - Wigley III model, \( \text{Fn} = 0.2 \)
  - Wigley III model, \( \text{Fn} = 0.3 \)
Results of Added Resistance (Series 60 hulls)

(a) Rankine panel method

- Series60 $C_B = 0.7, F_n = 0.222$

(b) Strip method
Results of Added Resistance (S-175)

(a) Rankine panel method
- Experiment (Fujii, 1975)
- Experiment (Nakamura, 1977)
- Direct Pressure Integration Method + RPM
- Momentum Conservation Method + RPM
- Short wave (Fujii & Takahashi, 1975)
- Short wave (Faltinsen et al., 1980)
- Short wave (Kuroda et al., 2008)

(b) Strip method
- S-175, Fn = 0.15
- S-175, Fn = 0.20
- S-175, Fn = 0.25
Component of Added Resistance

- Component of Added Resistance (Direct Pressure Integration Method + RPM)

(a) $Fn = 0.15$, S-175 containership

(b) $Fn = 0.20$, S-175 containership
Conclusions

- Added resistance on ships in waves is calculated by the two different numerical methods, **Rankine panel method** and **strip method**. These are combined with the **near-field method** and the **far-field method**.

- In the case of motion response, the frequency of the peak value in the strip method is slightly moved to the high frequency region. These tendencies are shown in the added resistance results. **This means that the motion response crucially affects the prediction of added resistance.**

- In low speed, results of added resistance which calculated by all methods are well agreed with experimental data, while in high speed, there is some discrepancies among computed results, especially peak value frequency of added resistance. In general, Rakine panel method gives better agreement with experimental data than strip method. **→ It is needed to choose proper method by considering ship speed.**
Conclusions (cont.)

- Generally, the added resistances that are calculated by strip methods show good correspondence with the experimental data; however, some discrepancy can be observed when the ship speed is high, and the ship hull is a relatively blunt body.
  
  → If the ship does not have a blunt shape and high speed, the strip method is a good practical tool for the calculation of added resistance.

- According to the present case of added resistance in short waves, all methods (Fujii and Takahashi (1975), Faltinsen et al. (1980) and Kuroda et al. (2008)) give reasonable agreements with experimental data for a relatively blunt body, while only the method of Kuroda et al. (2008) gives reasonable results for a slender ship.

  → It is necessary to choose a proper method with respect to the shape of the ship.
Thank you!!