A simple alternative approach to assess the effect of the above-water bow form on the ship added resistance

Ming-Chung Fang*, Yi-Zi Lee, Kao-Tuao Huang

Department of Systems and Naval Mechatronic Engineering, National Cheng Kung University, Tainan, Taiwan, ROC

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ABSTRACT

In the paper, a simple alternative approach to assess the effect of the above-water bow form on the added resistance for the ship advancing in longitudinal waves is investigated. The strip theory and source distribution method are applied to solve the corresponding boundary conditions and analyze nonlinear motions and mean added resistance. In order to calculate the instantaneous ship motions and nonlinear forces with respect to the different draft, the time domain simulation technique based on the 4th Runge–Kutta method is applied here, and the instantaneous mean added resistance for a ship with different bow flare can be further obtained. The “total quasi-mean added resistance” is then defined to assess the virtual effect of the above-water bow flare shape. The present results show that the larger the bow flare, the larger the added resistance. The effect of wave profile along the ship length on the added resistance is also deeply investigated for discussions in the study.

1. Introduction

Many related seakeeping problems such as wave-induced motions and wave loads for the ship sailing at sea have been solved by lots of authors using either the two-dimensional theory, e.g., (Korvin-Kroukovsky, 1995; Salvesen et al., 1970 and Kim et al., 1980), or the three-dimensional theory, e.g., (Chang, 1977; King et al., 1988 and Alexander and Josh, 2001). In the past, most of the authors usually analyzed the problems in frequency domain because of simplicity and quickness. Recently the time domain simulating techniques were also submitted by several authors to make the seakeeping solutions more realistic, e.g., (King et al., 1988; Fang et al., 1993 and Yasukawa, 2000). Generally most of the authors calculated the related hydrodynamic coefficients based on the underwater hull configuration at the mean draft instead of considering the real resultant wave profile along the ship length caused by incident wave, diffraction wave and radiation wave. However, the real resultant wave profile is important for analyzing the dynamic stability, ship structural dynamic response, water shipping problem or added resistance if the underwater hull shape significantly changed with ship motions. Therefore, if the large amplitude motion is considered, the above-water hull shape might submerge into the water due to the relative wave elevation and consequently affect all the related hydrodynamic forces, and then the ship dynamic behaviors. In order to understand the effect of the above-water bow form on the ship seakeeping characteristics, the nonlinear approach for analyzing the ship motions is required. For example, the nonlinear ship motion simulation method in waves has been developed by Vinje and Brevig (1981) and Tanizawa (1995), and the more stable numerical approaches considering the instantaneous hull geometry in the body surface condition were presented by Lin and Yue (1990) and Kataoka et al. (2001).

The effects of the above-water bow form on the ship motions, drifting force, water shipping and added resistance have been studied by several authors. Fang (1995) made theoretical and experimental studies on the motions of the SWATH ship with different above-water bow flare. The results indicate that the small flare is advantageous to the vertical motions of the SWATH ship. Buchner (1996) studied the influence of the bow shape of FPSO on the drift forces and green water, and he concluded the mean wave drift force for shaper alternative bows seems smaller than the traditional bow. Later he also submitted a new method to analyze the nonlinear relative motions (Buchner, 1998). Kihara et al. (2005) applied the nonlinear slender body theory to analyze the effect of the above-water bow shape on the added resistance and he indicated that the added resistance increases with the bow flare angle. Since the ship motions cannot be directly simulated in their code, they must calculate the motions in advance for the prediction of added resistance. This technique might not be rational.

Recently some new studies about the added resistance were already submitted. Jonquez et al. (2008) solved the added resistance by a potential flow boundary element method in frequency domain, and compared the results between momentum-conservation approach and direct pressure integration. Kashiwagi (2009) used an enhanced unified theory to calculate the added resistance by a modified version of Maruo’s approach and quite satisfactory results were obtained. Kim et al. (2010) applied the two time-domain Rankine panel methods to compute the added resistance. Their study included the comparisons of Neumann–Kelvin and
Double-body linearizations, and the results were validated by comparing with the experimental data of some ship models. The contributions of radiation and diffraction components on the added resistance were also investigated. Kashiwagi (2010) applied not only the numerical calculations but also the measurements of the ship-generating unsteady waves to validate the wave analysis method for predicting the added resistance and the effects of local wave and lateral distance for the wave measurement were also studied. Later, in order to investigate which component of the ship-generating unsteady waves is dominate in the added resistance, Kashiwagi et al. (2011) based on the measurements of unsteady waves, i.e., in diffraction and radiation problems, and the subsequent unsteady wave analysis using the Fourier transform to compute the added resistance. They concluded that the large ship motions may generate some nonlinear local waves which will cause a noticeable discrepancy in the added resistance between the direct measurement and wave analysis. More recently, incorporating with a frequency domain 3D panel method and a new hybrid time domain Rankine source—Green function method of NTUA-SDL, Liu et al. (2011) calculated the added resistance by Maruo’s far-field method. The results showed that their predictions of the added resistance of ships with slender and bulky hull form are fully satisfactory.

Generally most of the authors who studied the ship added resistance or the effect of the above-water shape on the added resistance usually based on the analysis in frequency domain instead of the time domain; however the time-varied change of the above-water bow shape in frequency domain cannot be treated realistically. Therefore the time domain simulation technique based on the 4th Runge–Kutta method combining with the general B-spline theory is applied in the present paper to calculate the time-varied mean added resistance and the relative wave elevation along the ship hull. Basically the technique of the time simulation is similar to Fang et al. (1993) except the way for obtaining the related hydrodynamic coefficients. In Fang et al. (1993), all the related hydrodynamic coefficients with respect to different drafts are calculated and stored as the data base in advance and interpolated in the simulation process. However, the present paper uses the B-spline technique, i.e., adopted from the commercial software-IMSL Fortran Library, to obtain the new source point distributions of the instantaneous underwater hull shape, and then the related hydrodynamic coefficients at any draft can be calculated directly. The present calculations of mean added resistance basically follow the method developed by Fang (1991) and the concept of “total quasi-mean added resistance” is then submitted in the paper to access the effect of the above-water bow form. Some interesting phenomena and conclusions are found in the study and discussed in the later sections.

2. Mathematical formulas

2.1. Equations of motions

Since the present study only treats the cases for the ship moving in longitudinal regular waves, only the coupled equations of motions for heave($\eta_3$) and pitch ($\eta_5$) are considered here and shown as below:

\[
(M_{33} + M'_{33}(t)\dot{\eta}_3 + N_{33}(t)\dot{\eta}_3 + B_{33}(t)\eta_3 + M'_{53}(t)\dot{\eta}_5 + N_{53}(t)\dot{\eta}_5 + B_{53}(t)\eta_5)\eta_3 = R e[\tilde{F}_3(t)e^{-i\omega t}]
\]

(1)

![Fig. 1](image1.png)

Fig. 1. The body plan for the above-water bow flare with $\beta = 5^\circ$ (dash line).

![Fig. 2](image2.png)

Fig. 2. The body plan for the above-water bow flare with $\beta = 7^\circ$ (dash line).

![Fig. 3](image3.png)

Fig. 3. The body plan for the above-water bow flare with $\beta = 15^\circ$ (dash line).
\[ M_{23}(t)\ddot{\eta}_3 + N_{23}(t)\dot{\eta}_3 + B_{23}(t)\eta_3 + (I_{SS} + M_{23}(t))\ddot{\eta}_5 + N_{SS}(t)\eta_5 + B_{SS}(t)\eta_5 = \text{Re}\{F_3(t)e^{-i\omega t}\} \]

In Eqs. (1) and (2), all hydrodynamic coefficients, i.e., the added mass \(M^a\), damping coefficients \(N\), exciting forces \(F\) and restoring forces \(B\), varied with time because the draft changes with the motions at any instant time. Consequently the underwater hull shape of the ship changes with time due to the relative motion between ship hull and wave. Then the above-water bow form will play an important role to affect the hydrodynamic coefficients when it submerges into the water. In the above equations, \(M\), \(I\) and \(\omega\) represents the ship mass, mass moment inertia and wave encounter frequency, respectively.

### 2.2. Hydrodynamic pressure and relative wave elevation

The resultant hydrodynamic pressure on the ship hull for the ship moving with constant speed \(U\) in waves mainly consists of the incident wave pressure, \(P_i\), the diffraction pressure, \(P_d\), and the radiation pressure, \(P_r\), which can be derived as below, (Fang et al., 1993)

\[ P_i(x,t) = \text{Re}\{\rho g a e^{i\omega t}e^{i\eta_0 x} \cos \frac{\eta_0 x}{C_0} e^{-i\omega t}\} \]

\[ P_d(x,t) = \text{Re}\{\rho \omega \phi_0(t) e^{i\eta_0 x} a \cos \frac{\eta_0 x}{C_0} e^{-i\omega t}\} \]

\[ P_r(x,t) = \text{Re}\left\{\rho \left(\phi(t) + U \frac{\partial}{\partial x}\right) \hat{S}(x,t) \phi(t) e^{-i\omega t}\right\} \]

**Fig. 4.** The time simulation of motions and mean added resistance with different wave amplitude \((\omega_0=0.384 \text{ rad/s} \ \beta=0^\circ)\).
where \( \rho, g, a, \nu_o, \mu \) and \( \omega_o \) are water density, gravitational acceleration, wave amplitude, wave number, wave heading and wave frequency, respectively. \( \phi_D \) and \( \phi_R \) are diffraction wave potential and radiation wave potential, respectively, and can be solved by using the source distribution method, i.e.,

\[
\phi_{D,R}(y,z) = \int_C Q(\eta, \zeta) G(y,z; \eta, \zeta; \nu_o) dC
\]

(6)

The detailed derivations of both wave potentials can be found in Kim et al. (1980). In Eq. (6), the Green function \( G \) is the two-dimensional pulsating source potential of unit intensity at the point \( (\eta, \zeta) \). The \( C \) indicates that the integral is to be taken along the underwater hull section contour. The distributed unknown source intensities \( Q \) along the contour \( C \) are determined by satisfying the following related boundary conditions on the underwater wetted surface,

\[
\frac{\partial \phi_D}{\partial n} = -\frac{\partial \phi_i}{\partial n}
\]

(7)

\[
\frac{\partial \phi_R}{\partial n} = v_n
\]

(8)

where \( \phi_i \) is the incident wave potential and \( v_n \) is the normal velocity of a point on the wetted hull surface.

However, both potentials are time-varied since the underwater hull shape changes with the ship motions. Consequently the source distributions of the underwater hull shape are also time-varied and must be solved to calculate the related wave potentials with respect to the different draft at any instant time. The \( S(x, t) \) in Eq. (5) represents the instantaneous vertical motion

Fig. 5. The time simulation of motions and mean added resistance with different wave amplitude (\( \omega_o=0.384 \, \text{rad/s}, \, \beta=15^\circ \)).
displacement at any position $x$ and can be expressed as

$$S(x,t) = \eta_3(t) - x\eta_5(t) + \frac{iU}{\omega} \eta_7(t)$$

Substitute the Eq. (9) into the Eq. (5) and re-derive the pitch motion (Fang et al., 1993), we can obtain another representation for $P_R$ as below,

$$P_R(x,t) = \text{Re} \left\{ \left( \eta_3(t) - x\eta_5(t) - \frac{2U}{\omega^2} \eta_5(t) \right) i\rho \omega \phi_d(t)e^{-i\omega t} \right\}$$

The resultant instantaneous wave elevation at each strip ($x$) due to the incident wave, the diffraction wave and the radiation wave is then obtained by

$$\frac{P_{DS}(x,t)}{\rho g} = \frac{P_I(x,t) + P_D(x,t) + P_R(x,t)}{\rho g}$$

From Eq. (9), the vertical motion displacement for each strip can also be represented by

$$Z(x,t) = \eta_3(t) - x\eta_5(t) - \frac{U}{\omega^2} \eta_5(t)$$

The relative wave elevation with respect to the ship is

$$r(x,t) = \frac{P_{DS}(x,t)}{\rho g} Z(x,t)$$

Then the instantaneous draft of each strip ($x$) at any instant time $t$ can be obtained by

$$D_t(x,t) = d_0(x) + r(x,t)$$

where $d_0$ is the initial ship draft in calm water. Consequently, with the instantaneous draft of each section at each time step, we can automatically rearrange the source distribution with respect to the instantaneous new wetted hull body surface using the
B-spline technique. Then we solve the boundary value problem to calculate the related instantaneous hydrodynamic coefficients, e.g., added masses, damping coefficients, exciting forces and restoring forces in coupled equations of motions (1) and (2). In the calculation process, the resultant relative wave surface at each strip is always assumed to be the still water surface and the new source distribution along the new underwater hull section contour can then be reconstructed below the still water surface.

2.3. The “mean added resistance” and “total quasi-mean added resistance”

While the ship moving in waves, there exist extra nonlinear hydrodynamic forces on the ship hull, which are so called added resistance and lateral drifting force. The added resistance is the longitudinal component which directly contributes to the ship speed loss. Generally the added resistance calculated in frequency domain is represented as a “mean” value in the following Eq. (15) (Fang, 1991), i.e., mean added resistance,

\[ F_A = \text{Re} \left\{ \frac{i}{2} \rho V_0 \left[ \int \int_S \sum_{j=2}^{6} \eta_j \phi_R^{(j)} + \phi_D \frac{\partial \phi_I^*}{\partial n} \, ds \right. \right. \]

\[ \left. \left. - \int \int_S \sum_{j=2}^{6} \eta_j \phi_R^{(j)} + \phi_D \right) \phi_I^* \, ds \right\} \cos \mu \]

where \( \eta_j \) is the jth motion mode and the subscript \( j=2, 3, 4, 5, 6 \) represents sway, heave, roll, pitch and yaw, respectively. \( \phi_R^{(j)} \), \( \phi_D \) and \( \phi_I^* \) are the radiation wave potential, the diffraction wave potential and the complex conjugate of incident wave potential, respectively. In Eq. (15), the surge motion is assumed to be small.

\[ \text{Fig. 7.} \text{ The time simulation of motions and mean added resistance with different wave amplitude (} \omega_0 = 0.478 \text{ rad/s, } \beta = 15^\circ \text{).} \]
and neglected. Because only longitudinal waves are considered in the study, the heave mode \( j = 3 \) and pitch mode \( j = 5 \) are considered here. In Eq. (15), \( \phi_0^h, \phi_D^h \) and \( \phi_0^p, \) heave(\( \eta_3 \)) and pitch (\( \eta_5 \)) are time-varied because the draft changes with time. Consequently \( F_A \) becomes the time-varied mean added resistance, i.e., \( F_A(t) \). In the present study, the time domain technique is adopted for analyzing the motions; therefore we can calculate the instantaneous underwater hull configuration at any time. Consequently the related time-varied mean added resistance based on the underwater hull configuration can be estimated for the ship moving in waves. However, in order to judge the integrated effect on the time-varied mean added resistance of the ship, we further define the following “total quasi-mean added resistance” to assess the integrated effect with respect to the different bow flare,

\[
F_{TA} = \frac{\int_0^T F_A(t) \, dt}{T}
\]  

(16)

Based on this “total quasi-mean added resistance” calculation, we may investigate the virtual consideration of the added resistance for the ship moving in waves at different draft.

3. Results and discussions

A container ship with the principal dimensions shown in Table 1 is adopted as the calculation model. In order to investigate
the effect of the above-water bow form on the motions and added resistance, we change the above-water bow form with different flare angle based on the original underwater ship hull configuration, i.e., $\beta = 0^\circ$.

The bow flares with different angles, i.e., $\beta = C0.5, 1, 3, 5, 7, 10^\circ, 15^\circ$, are considered for calculations and some configurations of them, i.e., $\chi = C0.6, 1.0, 1.4$ m, are shown in Figs. 1–3 for reference. Three different wave amplitudes, i.e., 0.6 m, 1.0 m, 1.4 m, and three different wave frequencies, i.e., 0.384 rad/s, 0.478 rad/s, 0.638 rad/s, are considered in the study, in which 0.478 rad/s is around the motion resonance frequency. All results discussed in the following figures are normalized by related parameters, i.e., $L$ (ship length), $B$ (Breadth), $a$ (wave amplitude), $\rho$ (water density) and $g$ (gravitational acceleration).

Table 2

<table>
<thead>
<tr>
<th>$\lambda/L$</th>
<th>$\omega_0$ (rad/s)</th>
<th>$\beta$ (°)</th>
<th>Frequency domain ($\eta_3/a$)</th>
<th>Time domain ($\eta_3/a$) ($a=0.6$ m)</th>
<th>Time domain ($\eta_3/a$) ($a=1.0$ m)</th>
<th>Time domain ($\eta_3/a$) ($a=1.4$ m)</th>
</tr>
</thead>
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<tr>
<td>2.25</td>
<td>0.384</td>
<td>0</td>
<td>0.97</td>
<td>0.98</td>
<td>0.99</td>
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<td>1.05</td>
<td>1.04</td>
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<tr>
<td>1.45</td>
<td>0.478</td>
<td>0</td>
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<td>1.07</td>
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<tr>
<td>0.82</td>
<td>0.638</td>
<td>0</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.19</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
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</table>

Fig. 9. The time simulation of motions and mean added resistance with different wave amplitude ($\omega_0 = 0.638$ rad/s, $\beta = 15^\circ$).
The time simulation results for the normalized motions and mean added resistance with respect to three different waves have been calculated and some of them are shown in Figs. 4–9 for reference. These results can be used for the further discussions on the ship total quasi-mean added resistance. From Figs. 4–9, it seems that the effects of wave amplitude on the motions are not

### Table 3

<table>
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<tr>
<th>λ/L</th>
<th>ω₀ (rad/s)</th>
<th>β (°)</th>
<th>Frequency domain (ϕₜ/av)</th>
<th>Time domain (ϕₜ/av) (a=0.6 m)</th>
<th>Time domain (ϕₜ/av) (a=1.0 m)</th>
<th>Time domain (ϕₜ/av) (a=1.4 m)</th>
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<td>2.25</td>
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<td>0</td>
<td>1.12</td>
<td>1.22</td>
<td>1.22</td>
<td>1.23</td>
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<td>1.22</td>
<td>1.22</td>
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<tr>
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<td>0.478</td>
<td>0</td>
<td>1.09</td>
<td>1.18</td>
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<td>0.638</td>
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<td>0.26</td>
<td>0.26</td>
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Fig. 10. The mean added resistance with respect to the different bow flare and different wave amplitude (ω₀=0.478 rad/s) (--- = β=15°, ------ = β=7°, — — — — β=0°, = = = β=−5°).
significant for both cases with and without bow flare at the present three frequencies. In order to investigate the nonlinear effect on motions more clearly, the calculated values of the motion response amplitude with respect to the frequency domain analysis and the time domain analysis are shown in Tables 2–3 for reference. The results reveal that the heave response is decreased as the wave amplitude is increased at $\omega_0=0.384$ rad/s and 0.478 rad/s. However, the nonlinear effect on the other cases is not significant. It is also found that the trend calculated by time domain analysis with respect to the different frequencies is similar to that calculated by frequency domain analysis, which can prove that the results by time domain analysis are physically reasonable. Besides, the motion response decreases with the bow flare for different wave amplitude around the resonance frequency, which means that the larger bow flare might be advantageous to the motion around the resonance frequency.

Although the wave amplitude generally has no significant effect on the motions, the results in Figs. 4–9 reveal that the peak values of the mean added resistance decrease with the increasing wave amplitude, but increase with the bow flare angle, especially for 0.478 rad/s in larger amplitude. If we normalize the Eq. (15) by $a^2$, the motion terms of radiation component in the right-hand side will be normalized to $n/a$ by one $a$, which means the motions would not significantly affect the added resistance; however, there still exists contributions from the radiation wave potential, $\phi_D^R$, and the complex conjugate of incident wave potential, $\phi_I^*$ and $\bar{\phi}_I$, in the radiation component. The diffraction wave potential, $\phi_D^D$, and complex conjugate of incident wave potential, $\phi_I^*$ and $\bar{\phi}_I$, will dominate in the diffraction component of the added resistance in the right-hand side of the equation. Therefore both components have the contributions on the variations of the added resistance with respect to the different

![Fig. 11](image1.png)

Fig. 11. The total quasi-mean added resistance with respect to the different wave amplitudes and bow flare angles ($\omega_0=0.384$ rad/s).

![Fig. 12](image2.png)

Fig. 12. The total quasi-mean added resistance with respect to the different wave amplitudes and bow flare angles ($\omega_0=0.478$ rad/s).
wave amplitude. The comparisons of the time histories of different bow flare angle for different wave amplitudes at 0.478 rad/s are shown in Fig. 10 for reference. It clearly shows the larger bow flare causes larger mean added resistance, i.e., the largest value at 15° and the smallest one at −5°.

Based on the time simulation results of the mean added resistance, the total quasi-mean added resistance with respect to different bow flare angles and wave amplitudes can be obtained and shown in Figs. 11–13 for different wave frequencies, respectively. The results show the total quasi-mean added resistance generally increases with bow flare angles, which agree with the conclusion of Kihara et al. (2005). Intuitively the added resistance is supposed to increase with the wave amplitude; however, it is interesting to find the opposite trend in present results which show the total quasi-mean added resistance with larger wave amplitude is smaller than those with smaller wave amplitude. This might be concluded to be a nonlinear phenomenon which is interesting but not strange. This nonlinear phenomenon can be explained using the time simulation results with respect to the different wave amplitudes in Figs. 4–9. From the results in Figs. 4–7, i.e., \( \omega_0 = 0.384 \) rad/s and 0.478 rad/s, we find that the positive mean added resistances is generally much larger than the negative one for the smaller wave amplitude, i.e., 0.6 m and 1.0 m, therefore the total quasi-mean added resistances are always positive and decreases with the increasing wave amplitude. In Figs. 8 and 9, i.e., \( \omega_0 = 0.638 \) rad/s, there is even smaller negative added resistance for smaller amplitude of 0.6 m whereas it is larger negative for 1.0 m and 1.4 m, therefore the total quasi-mean added resistance for the larger amplitude is also smaller. This nonlinear phenomenon is quite interesting but seems physically reasonable based on the above analysis. In order to more clearly investigate the effect of the different bow flare on the total quasi-mean added resistance in different waves, the related comparisons are also summarized in Tables 4–6. The results reveal that the total quasi-mean added resistance generally increases with the bow flare angle, especially around the motion resonance frequency, i.e., 0.478 rad/s. Therefore, we can conclude that the smaller positive bow flare angle or the negative one might be

### Table 4

<table>
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<tr>
<th>( \beta )</th>
<th>-5°</th>
<th>-3°</th>
<th>5°</th>
<th>7°</th>
<th>10°</th>
<th>15°</th>
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<tr>
<td>a 1.4 m</td>
<td>-2.27%</td>
<td>-1.90%</td>
<td>0.0%</td>
<td>0.43%</td>
<td>0.84%</td>
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<td>1.0 m</td>
<td>-1.41%</td>
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<td>-0.11%</td>
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### Table 5

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<th>( \beta )</th>
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<th>5°</th>
<th>7°</th>
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<td>7.42%</td>
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<td>2.24%</td>
<td>2.95%</td>
<td>4.85%</td>
<td>5.80%</td>
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<td>-0.17%</td>
<td>0.62%</td>
<td>1.11%</td>
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### Table 6

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<th>( \beta )</th>
<th>-5°</th>
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<th>5°</th>
<th>7°</th>
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<td>0.6 m</td>
<td>-0.29%</td>
<td>-0.07%</td>
<td>0.10%</td>
<td>0.22%</td>
<td>0.31%</td>
<td>0.83%</td>
</tr>
</tbody>
</table>

Fig. 13. The total quasi-mean added resistance with respect to the different wave amplitudes and bow flare angles (\( \omega_0 = 0.638 \) rad/s).
advantageous for the ship moving in waves from the point view of the added resistance.

Usually, as we know, the added resistance is the “extra resistance” due to the wave mechanism effect; therefore the relative wave elevations around the bow part and stern part should play important roles in the formation of the wave added resistance. Here we select the original hull shape as the example to explain this phenomenon in detail. The normalized relative wave elevations along the ship hull length with respect to the maximum and minimum values of the mean added resistance at different frequencies are shown in Figs. 14–19, respectively. The results of the normalized relative wave elevations are calculated based on the occurrence of the maximum and minimum mean added resistance, i.e., at $t = 73.5$ s, 79.2 s, 62.9 s, 67.2 s, 65.1 s and 68 s referring to Figs. 4, 6 and 8, respectively. Physically the ship encounters larger positive added resistance, i.e., resist the ship’s

![Fig. 14. The instantaneous relative wave elevation along the ship hull length with respect to different wave amplitudes ($\beta = 0^\circ$, $\omega_0 = 0.384$ rad/s, $t = 73.5$ s).](image)

![Fig. 15. The instantaneous relative wave elevation along the ship hull length with respect to different wave amplitudes ($\beta = 0^\circ$, $\omega_0 = 0.384$ rad/s, $t = 79.2$ s).](image)
forward movement, while the relative wave elevations are positive around the fore body and negative around the aft body. Conversely the negative added resistance occurs with positive relative wave elevations around the aft body and negative ones around the fore body, i.e., push the ship to move forward. Hence, the wave forms shown in Figs. 14, 16 and 18, i.e., positive bow wave and negative stern wave, cause maximum mean added resistances whereas those shown in Figs. 15, 17 and 19, i.e., negative bow wave and positive stern wave, cause minimum values. Those wave mechanism effects cause the results in Figs. 4, 6 and 8, consequently it can also be used to explain the nonlinear phenomenon stated before.

4. Conclusions

A series of analysis for the effect of the bow flare shape on the ship added resistance has been done using a simple alternative approach, i.e., total quasi-mean added resistance, in the present paper. According to the above analysis, some conclusions are drawn as below:

1. Generally the larger bow flare is disadvantageous for the ship added resistance.
2. According to the present study, the larger wave amplitude might cause less added resistance than the smaller wave,
especially around the motion resonance. This can be considered as the nonlinear phenomena and can be explained by the wave mechanism due to the resultant relative wave elevation along the ship length.

3. Although the large bow flare causes the large added resistance, it is generally advantageous for the water shipping problem realistically. Therefore the optimal design for the bow flare must be carefully considered based on different factors.

The simple approach based on the total quasi-mean added resistance defined here has been successfully applied to assess the effect of bow flare on the ship added resistance, which agrees with the conclusions from other researches based on different approaches. However, the present assessing approach is only based on the theoretical study; the validity is suggested to be further confirmed by the related experiments.

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References


Buchner, B., 1996. The influence of the bow shape of FPSOs on drift forces and green water. OTC, No. 8073.


