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# Numerical Investigation on the Water Entry of Several Different Bow-Flared Sections

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**Abstract:** The bow-flared section may be simplified in the prediction of slamming loads and whipping responses of ships. However, the difference of hydrodynamic characteristics between the water entry of the simplified sections and that of the original section has not been well documented. In this study, the water entry of several different bow-flared sections was numerically investigated using the computational fluid dynamics method based on Reynolds-averaged Navier–Stokes equations. The motion of the grid around the section was realized using the overset mesh method. Reasonable grid size and time step were determined through convergence studies. The application of the numerical method in the water entry of bow-flared sections was validated by comparing the present predictions with previous numerical and experimental results. Through a comparative study on the water entry of one original section and three simplified sections, the influences of simplification of the bow-flared section on hydrodynamic characteristics, free surface evolution, pressure field, and impact force were investigated and are discussed here.

Keywords: water entry; bow-flared sections; slamming; computational fluid dynamics

# 1. Introduction

Ship slamming is an important aspect that needs to be considered in the design of a bow-flared ship. The hydrodynamic impact between the ship hull and the water can cause local damage to the hull and induce global whipping responses [1-4].

In order to investigate the fundamental mechanisms during slamming, the water entry of two-dimensional (2D) ship sections or three-dimensional (3D) ship structures has been studied extensively. The pioneering work on water entry can be traced back to von Karman [5] and Wagner [6], which was motivated by seaplane landing problems. Zhao et al. presented a fully nonlinear boundary element method for simulating the water entry of an arbitrary section [7]. Sun and Faltinsen [8] studied the 2D water entry of a bow-flared section with a constant roll angle using a boundary element method, and their numerical results were compared with the experiments [9]. Wang and Guedes Soares simulated the asymmetric water entry of a bow-flared ship section with a roll angle using the arbitrary Lagrangian–Eulerian solver in LS-DYNA [10]. Yang et al. numerically investigated the water entry of a wedge and a ship section using an incompressible immersed boundary method [11]. Xie and Ren comprehensively studied the effect of geometrical asymmetry and kinematic asymmetry on hydrodynamics during the water entry of a bow-flared ship section [12]. Yu et al. [13] simulated the water entry problem of curved wedges, and the numerical method was validated by comparison with the experimental results reported by Panciroli et al. [14]. The influence of curvature on the impact force, slamming pressure distribution, and wetted width was numerically investigated. Chen et al.

investigated the effect of ice on impact loads during the water entry of a wedge using both computational fluid dynamics (CFD) and a Wagner-type theoretical model [15].

Numerical simulations of slamming loads and whipping responses of a ship in waves can be found in many recent papers. Hermundstad and Moan analyzed bow-flared slamming on a Ro-Ro vessel in regular oblique waves [16]. The motion of the ship and bow-flared slamming loads were solved. Ignoring the influence of slamming loads on the motion of the ship, the relative motion between the ship and the wave was calculated using a nonlinear strip theory. Then, bow-flared slamming loads were calculated using a slamming program that was based on a generalized Wagner formulation and solved by a 2D boundary element method. For the section with a bulbous bow, flow separation may occur at the bulbous bow during the water entry, and the separated fluid may impact the hull surface again. This phenomenon is usually called "secondary slamming" [10,12]. It is difficult to use the boundary element method to reasonably analyze the secondary slamming phenomenon. Therefore, Hermundstad and Moan proposed three simplified sections for the prediction of slamming loads instead of the original bow-flared section [15]. Tuitman et al. investigated the local structural response due to seakeeping and slamming loads [17]. The seakeeping analysis was conducted using a linear 3D boundary element method. The slamming loads were calculated using the 2D generalized Wagner model, and the original bow-flared section was simplified. Kim et al. also simplified the original bow-flared section in hydroelastic analysis of a container ship [18].

Meanwhile, the CFD method based on Reynolds-averaged Navier–Stokes (RANS) equations has been adopted for the prediction of both slamming pressure and hydroelastic response. Chen et al. predicted the bow-flared slamming pressure and the bottom slamming pressure of an oil tanker under extreme motion conditions using the CFD software StarCCM+ [19]. The predicted pressure was compared with the pressure obtained from harmonized common structural rules (CSR-H), and it was found that the slamming pressures defined by CSR-H were safe and conservative with regard to the structural design. Seng et al. developed a global hydroelastic model for the prediction of springing and whipping responses of flexible vessels [20]. The flow field inside the fluid domain was solved using the open-source CFD software package OpenFOAM. Structural deformation was described by a modal superposition of dry mode shapes expressed in a local floating frame of reference. The interaction between the fluid solver and the structural solver were in a strongly coupled scheme. Dhavalikar et al. developed a one-way fluid structure interaction method for the whipping response of a hull girder [21]. Hydrodynamic loads were calculated using the CFD solver StarCCM+. Added mass was estimated by empirical formulation, while transient structural response was solved using the mode superposition method. The slamming pressure and the whipping response showed good agreement with the published experimental results [22]. Takami et al. developed a one-way coupling model to simulate hydroelastic response under severe wave conditions [23]. Commercial solvers StarCCM+ and LS-DYNA were used to solve the fluid domain and the structural response, respectively. The whipping response of the hull girder and the local dynamic response of the double bottom structure were simulated.

Compared with the CFD method based on RANS equations, slamming loads can be predicted more quickly using the boundary element method (BEM) based on the potential flow theory, especially for the simulation of slamming loads and whipping responses of ships in waves. However, it is difficult to use BEM to correctly predict the secondary slamming phenomenon. Therefore, it is inevitable to use simplified sections to replace the original hull section for prediction of slamming loads ([16–18]). For a bow-flared section with a bulbous bow, Hermundstad and Moan presented three simplified sections [16]. However, the simplification of the original section may lead to deviation in predicting slamming loads due to inaccurate prediction of the separation point using BEM. To our knowledge, the difference in hydrodynamic characteristics during the water entry of the simplified sections and the original section has not been well documented. In this study, the water entry of several different bow-flared sections, including the original section and the simplified sections, was numerically investigated using the CFD method based on RANS equations. The validity of the CFD method was

checked by comparing the predicted results with published experimental data under the same flow conditions. The influences of simplification of the bow-flared section on hydrodynamic characteristics, free surface evolution, pressure field, and impact force were investigated and are discussed here.

#### 2. Mathematical Formulation and Numerical Methods

Referring to previous studies on the water entry of ship sections [11,12] and asymmetric wedges [24,25], two fluids (water and air) were assumed to be immiscible and incompressible. Then, the RANS model consisting of the time-averaged instantaneous continuity and momentum equations can be written as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + v \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \overline{u'_i u'_j}$$
(2)

where  $u_{i,j}$ ,  $i, j \in [1, 2, 3]$  denotes the time-averaged velocity components in the  $x_1, x_2$ , and  $x_3$  directions, respectively;  $(x_1, x_2, x_3) = (X, Y, Z)$ ;  $f_i$  is the time-averaged body force;  $u'_i$  and  $u'_j$  are the fluctuating velocity components;  $\overline{u'_i u'_j}$  is the Reynolds stress tensor, which is sometimes expressed as  $\tau_{ij}$ ; v is the kinematic viscosity of the fluids;  $\rho$  is the density of the fluids; and p is the time-averaged pressure.

The interface between air and water was captured using the volume of fluid (VOF) technique [24]. An effective fluid representing the two-phase flow of water and air was introduced to solve the RANS model. Effective density  $\rho_{eff}$  and effective viscosity  $\nu_{eff}$  can be calculated using the following equations:

$$\rho_{eff} = \gamma \rho_1 + (1 - \gamma) \rho_2 \tag{3}$$

$$v_{eff} = \gamma v_1 + (1 - \gamma) v_2 \tag{4}$$

where  $\rho_1$  and  $\nu_1$  are the density and viscosity of air, while  $\rho_2$  and  $\nu_2$  are the density and viscosity of water.  $\gamma$  is the volume fraction of air;  $\gamma = 0$  denotes that the fluid in the cell is water, whereas  $\gamma = 1$  is air. If  $0 < \gamma < 1$ , it means that a combination of air and water exists in the cell. By means of Equations (3) and (4), the property of a cell can be predicted. The governing equation of  $\gamma$  is as follows:

$$\frac{D\rho}{Dt} = 0 \rightarrow \frac{D(\gamma \cdot \rho_1 + (1 - \gamma)\rho_2)}{Dt} = 0$$
(5)

$$\frac{D\gamma}{Dt} = \frac{\partial\gamma}{\partial t} + u \cdot \nabla\gamma = 0 \tag{6}$$

The commercial CFD solver StarCCM+ was used to solve the RANS model. The chosen turbulence model was realizable k-epsilon two-layer turbulence model by referring to previous studies [24,26]. Temporal integration was carried out using the Euler implicit scheme. The governing equations were discretized using the central difference scheme in space except the convection term, which used a second-order upwind scheme. The segregated flow solver based on the semi-implicit method for pressure-linked equation (SIMPLE) algorithm was used to solve the pressure and velocity coupling problem during the water entry. The motion of the grid around the ship section was numerically realized using the overset mesh method, and the transfer of physical quantities between the overset zone and the background zone was realized using the linear interpolation method.

#### 3. Computational Overview, Convergence, and Validation Studies

#### 3.1. Computational Overview

The bow-flared sections considered in the present study were symmetrical, and their motion was limited to the vertical direction. Therefore, only half of the model was established. As shown in Figure 1, the computational domain was rectangular. In the figure, the vertexes of the rectangle

are marked as A, B, C, and D. A Cartesian coordinate system OXY was introduced to describe the numerical model. The OX axis was located at the undisturbed water surface, and the OY axis lied in the symmetrical axis of the bow-flared sections. In the figure, the dimension of the computational domain in the XY plane is noted as L1, L2, and H, while W is the half-width of the bow-flared sections. Referring to the discussion on the size of the computational domain [24,27], the lengths of L1, L2, and H were set as 8, 4, and 10 W, respectively.



Figure 1. Schematic diagram of the computational domain.

The boundary conditions of the numerical model were set as follows. The boundary condition of "AB" was set to pressure outlet. Only air was allowed to exit the domain. The boundary conditions of "BC" and "CD" were set to velocity inlet, where the velocity and the composition of field component (air and water) were specified. Only water was allowed to enter into the boundary "CD". The boundary condition of "AD" was set to symmetry boundary. The boundary condition of the ship section was set to no-slip wall.

Figure 2a shows the mesh view of the global domain. An overset mesh was applied to model the motion of the bow-flared section, and it is shown in black color in Figure 2a. The motion of the bow-flared section was specified in accordance with the velocity curve. In order to accurately simulate

the interaction between the section and the water, fine mesh was assigned to the region where the section might pass. Figure 2b shows the fine mesh near the section.



Figure 2. Mesh domain: (a) global domain; (b) view of grid structures.

# 3.2. Convergence Study

Studies were carried out to evaluate the effects of grid resolution and time step on the calculated results. Figure 3 shows the bow-flared sections; only half of the section is shown due to the symmetry. Two typical sections, "S1" and "S2", were examined in the grid resolution test. In the figure, P1, P2, and P3 are the locations for pressure monitoring. Figure 4 shows the velocity curve of the bow-flared section entering into the water, which was derived from the model test of the ship in waves [16].

Table 1 shows the number of grids and time steps for four different sets of simulations. Figure 5 shows impact forces and impact pressures of section "S1" with different mesh densities and the corresponding time steps. Figure 6 shows impact forces and impact pressures of section "S2" with different mesh densities and the corresponding time steps. It can be seen that there were obvious differences between the results of the M1 case and the M3 case. With the decrease of grid size, the deviation of the predictions between different grid configurations decreased, and the results of the M3 case and the M4 case are in good agreement. Considering both the accuracy of results and the time consumed in the present work, M3 was used in the following studies.

Case	Minimum Grid Size (m)	Time Step (s)	Total Number of Grids
M1	0.005	0.001	35,476
M2	0.0025	0.0005	125,148
M3	0.00125	0.00025	219,069
M4	0.000625	0.000125	448,163

**S**1

y (m)

 Table 1. Information for four different sets of simulations.



Figure 4. Velocity curve of the bow-flared section.



**Figure 5.** Impact forces and impact pressures of "S1" with different mesh densities: (**a**) impact force; (**b**) P1; (**c**) P2; (**d**) P3.



Figure 6. Cont.



**Figure 6.** Impact forces and impact pressures of "S2" with different mesh densities: (**a**) impact force; (**b**) P1; (**c**) P2; (**d**) P3.

#### 3.3. Validation Studies

Considering that the secondary slamming phenomenon may appear during the water entry impact of a bow-flared section, the two previous drop tests were simulated using the present method, which corresponded to the water entry without and with the secondary slamming phenomenon, respectively.

The shape of the bow-flared section in the drop test by Aarsnes [9] is shown in Figure 7. The section was symmetrical, so only half of the section is shown. P4–P7 are the positions where the pressure sensors were installed. The total weight of the falling rig was 261 kg. The total length of the ship bow section was 1.0 m. The initial impact velocity was 2.43 m/s, corresponding to the time when the section touched the still water surface. Figure 8 shows a comparison between the experimental results of Aarsnes [9] and numerical results. Because Aarsnes's section had no obvious bulbous bow structure, the second slamming phenomenon did not appear in the process of water entry. Sun and Faltinsen [8] validated the nonlinear boundary element method by comparison with Aarsnes's drop tests, and the results of the boundary element method are also shown in Figure 8. As can be seen in the figure, the numerical results obtained by the present method are in good agreement with the experimental results reported by Aarsnes [9] and the numerical results reported by Sun and Faltinsen [8]. Because the three-dimensional effect in the drop tests was not taken into account in the present numerical simulation and in the study by Sun and Faltinsen [8], the numerical results obtained by the present method are closer to those reported by Sun and Faltinsen [8], especially for the impact pressure of P5, P6, and P7.

In the Wave Induced Loads on Ships (WILS) Joint Industry Project [28], a drop test of a symmetrical bow-flared section was performed. The profile of half section is shown in Figure 9. Unlike the bow-flared section of Aarsnes [9], the profile in Figure 9 has an obvious bulbous bow structure. P8 and P9 are the positions where the pressure sensors were installed. The initial impact velocity was 2.43 m/s. Figure 10 shows the free surface elevations obtained by the present numerical study and the drop test. It can be seen that the present numerical method could reasonably predict the free surface elevation near the dropping section, and the second slamming phenomenon caused by the bulbous bow structure was also well simulated. Figure 11 shows the contrastive results for the water entry of MOERI's bow-flared section. The results of the immersed boundary method in the work of Yang et al. [11] are also shown in Figure 11. It can be seen that even if the second slamming phenomena appeared, the present numerical method could reasonably predict the impact pressure on the dropping section.



Figure 7. Shape of the bow-flared section in the drop test by Aarsnes (1996).



Figure 8. Cont.





**Figure 8.** Comparison between experimental results of Aarsnes (1996) and numerical results: (**a**) force; (**b**) velocity; (**c**) acceleration; (**d**) P4; (**e**) P5; (**f**) P6; (**g**) P7.



Figure 9. Shape of the bow-flared section in MOERI (2013).





(b)



(c)



**Figure 10.** Free surface elevations obtained by the present numerical method and the drop test in MOERI (2013): (a) the drop test (0.24 s); (b) the present method (0.24 s); (c) the drop test (0.26 s); (d) the present method (0.26 s).



Figure 11. Contrastive results for the water entry of MOERI's bow-flared section: (a) P8; (b) P9.

#### 4. Results and Discussions

The water entry of several different bow-flared sections, including the original section and the simplified sections, was simulated using the validated numerical method. The profiles of the sections are shown in Figure 3. In the figure, S1 is the original bow-flared section, and S2–S4 are the three simplified bow-flared sections given by Hermundstad and Moan [16]. The motion of the sections was specified by the same velocity curve, as shown in Figure 4. Then, the free surface evolution, pressure field, and impact force during the water entry of different bow-flared sections were comparatively studied.

# 4.1. Free Surface Evolution

Figures 12–15 show the free surface evolution during the water entry of different bow-flared sections. For the water entry of the original section S1, the free surface was separated from the section at the bulbous bow location. Then, the separated fluid impacted on the section again. In the process of secondary slamming, a small amount of air was captured, and a cavity was formed in the flow field. For the water entry of the simplified bow-flared sections, the free surface was gradually raised along the section, and the secondary slamming did not appear, as shown in Figures 13–15.

As shown in Figure 3, the original section and the simplified sections had the same bow-flared profile when y was greater than 0.4, while the simplified section S3 had a larger width when y was smaller than 0.4. In order to analyze the influence of different simplified options on water surface elevation, wetted length and pile-up coefficient were introduced and comparatively studied. Figure 16 illustrates the wetted length  $r^*$  and the reference wetted length r corresponding to the penetration depth  $\xi$ . The pile-up coefficient  $\phi r$  is defined as  $\phi r = r^*/r$ . It should be noted that the penetration depth of different sections is defined as the depth of the origin of the coordinate system XOY entering into the still water surface. Therefore, the lowest point of section S4 just touched the still water surface when the penetration depth  $\xi$  was 0.248 m.



Figure 12. Free surface evolution during the water entry of the modified section "S1".





Figure 13. Free surface evolution during the water entry of the original section "S2".



Figure 14. Free surface evolution during the water entry of the modified section "S3".



Figure 15. Free surface evolution during the water entry of the modified section "S4".



**Figure 16.** The wetted length  $r^*$  and the reference wetted length r corresponding to the penetration depth  $\xi$ .

Figure 17 shows the wetted length as a function of the penetration depth for different sections. With the increase of penetration depth, the water surface gradually rose along the section and the wetted length of different sections gradually increased. For a certain penetration depth, the wetted lengths of sections S3 and S4 were significantly larger and smaller than the wetted length of the original section S1, respectively. This was because the modification of section S3 and section S4 significantly increased and decreased the area of the lower part of the original section, respectively. The change

of the displacement at the lower part of the section further affected the increase of free surface in the bow-flared region during the water entry. Figure 18 shows the pile-up coefficient as a function of the penetration depth for different sections. It can be seen that the pile-up coefficient of section S2 was closest to that of the original section S1. The value of the pile-up coefficient of sections S1, S2, and S3 was obviously larger than that of  $\pi/2$  predicted by Wagner [6] for wedges, which was due to the obvious curvature change in sections S1–S3. Because the shape of section S4 was approximately wedge-shaped, the pile-up coefficient of section S4 was close to  $\pi/2$ .



Figure 17. The wetted length as a function of the penetration depth for different sections.



Figure 18. The pile-up coefficient as a function of the penetration depth for different sections.

#### 4.2. Pressure Field

Figure 19 shows the pressure distribution on the wetted surface for different sections. The abscissa is the vertical coordinate of each position on the section in the XOY coordinate system. At time t = 0.225 s,

the impact pressure of the original section was significantly higher than that of the simplified sections. In the secondary slamming phenomenon of the original section, the water separated at the bulbous bow will impact the bow-flared section again. As shown in Figure 12, the interface of the separated water was approximately parallel to the profile of the section. According to studies on water entry of wedges [6,29], a smaller dead rise angle will induce a larger impact pressure during water entry with the same impact velocity. Therefore, a large impact pressure is generated in the process of secondary slamming. Because there was no secondary slamming phenomenon in the water impact of the simplified sections, the pressure value at time t = 0.225 s of the simplified sections was relatively small. At subsequent times, the pressure distributions of different sections were generally close together. The pressure value of section S2 was slightly larger than that of section S3.

Figure 20 shows the history of the impact pressure of different positions. It can be seen that the secondary slamming phenomenon had a significant effect on the pressure at position P1. The P1 pressure value given by the original section S1 was significantly larger than that given by the simplified sections. For the pressure at P2 and P3, the impact pressures given by different sections were generally close. For the pressure peak at P2 of the original section, section S3 was underestimated by 14.1%, and section S2 and section S4 were overestimated by 1.8% and 22.6%, respectively. For the pressure peak at P3 of the original section, S2, S3, and S4 were underestimated by 5.8%, 32.6%, and 4.2%, respectively.



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Figure 19. Cont.



**Figure 19.** Pressure distribution on the wetted surface for different sections: (**a**) t = 0.225 s; (**b**) t = 0.2375 s; (**c**) t = 0.25 s; (**d**) t = 0.2625 s; (**e**) t = 0.275 s; (**f**) t = 0.2875 s.



Figure 20. History of the impact pressure of different position: (a) P1; (b) P2; (c) P3.

#### 4.3. Impact Force

Figure 21 shows the history of the impact force for different sections. In the initial stage of the water entry (t < 0.07 s), the impact force given by section S3 was consistent with the original section S1. Due to the simplification of the bulbous bow, the impact forces given by sections S1 and S4 deviated significantly from the impact force given by the original section in the initial stage. Due to the secondary slamming phenomenon, the impact force given by the original section S1 showed a distinct peak near time t = 0.2 s, which did not appear in the impact force given by the original profile showed a peak again. A similar peak appeared in the impact forces of the simplified sections. For the peak value of the impact force near time t = 0.28 s, section S3 was overestimated by 4.5%, and sections S2 and S4 were underestimated by 2.9% and 17.4%, respectively, compared to the original section.



Figure 21. History of the impact force for different sections.

# 5. Conclusions

The original bow-flared section needs to be simplified when BEM based on the potential flow theory is adopted in studies about slamming loads and whipping responses of ships ([16–18]). In the present study, water entry of several different bow-flared sections, including the original section and the simplified sections, was numerically investigated using the CFD method based on RANS equations. The objective of the present study was to evaluate the difference between the simplified sections and the original section on the slamming loads using the validated CFD method. The simplified sections corresponded to three different alternatives. The motion of the sections was specified according to a previous ship model test [16]. Reasonable grid size and time step were determined through a convergence study. The numerical method was validated by comparison with published free-fall drop tests ([9,28]).

Due to the influence of the bulbous bow, the secondary slamming phenomenon may appear during the water entry of the original bow-flared section. For the water entry of simplified sections, the free surface was gradually raised along the section, and secondary slamming did not appear. Compared with the other two simplified sections, the pile-up coefficient of section S2 was closer to that of the original section.

In the secondary slamming process, the free surface separated from the bulbous bow may form a small angle with the surface of the bow-flared section, thereby arousing greater slamming pressure and slamming force. However, the slamming loads caused by secondary slamming cannot be reasonably reflected when simplified bow-flared sections are adopted. After secondary slamming, the pressure distributions of different simplified sections were close to that of the original section. For the position away from the bulbous bow, the slamming pressure was less affected by the secondary slamming phenomenon.

The secondary slamming phenomenon caused two peaks in the slamming force of the original section, while all the simplified profiles could not give a reasonable prediction of the first peak value. For the second peak, the simplified sections could give a relatively reasonable prediction. Compared with the other two simplified sections, the slamming force of section S3 was closer to that of the original section, especially to the impact force at the initial stage and the second peak value of the impact force.

In general, by considering different impact forces of different simplified sections, the simplified section S3 would be the best choice when it is necessary to simplify the original bow-flared section. Although simplified sections cannot reflect the secondary slamming phenomenon of the original bow-flared section, the slamming force of the simplified section S3 was very close to that of the original section, except for the first peak caused by the second slamming phenomenon. Therefore, in studying global nonlinear motions and whipping responses of ships, the simplified section can give good predictions. However, the secondary slamming phenomenon can generate large slamming pressure near the bulbous bow, which could cause damage of the local structure. Therefore, it may be unsafe to use the slamming pressure provided by the simplified section for designing the local structure of a ship bow. In subsequent research, a prediction formula of slamming pressure considering the influence of secondary slamming will be given by regressing the CFD results of a series of bow-flared sections with bulbous bow, which could be useful for designing the local structure of a ship bow.

In the present study, two fluids (water and air) were assumed to be immiscible and incompressible by referring to previous studies on the water entry of ship sections [11,12]. Further research is needed to examine the effect of air compressibility on hydrodynamics during the water entry of a ship section.

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