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Effect of Spray Rails on Slamming Loads in High-Speed Planing Hulls under Symmetric and Asymmetric Water Entry

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ABSTRACT

Planing hulls are common on high-speed patrol boats, racers, and search and rescue boats because they can reach higher speeds by raising the hull above the water. This hydrodynamic lift, however, also causes more frequent and more severe slamming impacts, which can result in structural damage, malfunction of the equipment and injury to the passengers. Spray rails are usually installed to limit spray and enhance performance but there is little understanding of their effect on slamming loads. The present study examines slamming pressures and vertical accelerations generated during symmetrical and asymmetric water entry when using spray rails with a validated Computational Fluid Dynamics (CFD) model of a wedge-type planing hull section. The results indicate that slamming pressures are up to 45% higher in an area of the vessel when equipped with spray rails, but lower in another area, while peak vertical vessel accelerations are 38% higher in certain areas, especially under symmetric entry conditions. Asymmetric water entry leads to more unequal pressure distribution with high peaks opening earlier at the bottom of the hull, and to more steep vertical acceleration responses with increasing heel angle. The findings offer new insights into the complex role of spray rails in slamming behavior, which is vital in improving performance and safety of high-speed planing vessels.

1. Introduction.

Planing hulls are widely used in commercial and military marine applications including patrol enforcement, emergency rescue and offshore racing. They are capable of attaining high speeds because of the hydrodynamic lift created in their motion, which minimizes the wetted surface area and resistance to motion due to partial lifting of the hull (Tavakoli et al., 2024). This operational advantage comes at the expense of the vessel being exposed to slamming, an impact phenomenon that may occur when the hull leaves the water due to wave action and re-enters the water with a high vertical velocity (Faltinsen, 2005). These pressure fluctuations may cause structural damage, damage to onboard systems and safety concerns for crew and passengers, as highlighted by Abd Samad et al. (2021). Wang and Soares (2017) have mentioned that the criticality of slamming depends significantly on the hull form, ship speed, sea conditions, and ship orientation to the waves.

Accurate prediction of slamming loads is a difficult task because of the nonlinear and transient way the loads are generated by water impact, and the significantly different pressure distributions along the hull surface. Although some slamming investigations use full scale models (Li et al., 2024) but using such models under realistic sea conditions is computationally demanding and often impractical. To address this, researchers frequently use simplified models involving two-dimensional hull sections entering calm water, which allow the isolation of seakeeping analysis for determination of vessel kinematics and the study of individual parameters that govern slamming behavior (Wang and Soares, 2014, Xin et al., 2022, Zou et al., 2024).

Theoretical models of water entry started with the classical

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models of Von Karman (1929) and Wagner (1932), who developed analytical solutions to water entry problems in idealized conditions for wedge-shaped entries. The theory of slamming phenomena was further developed by Trilling (1950), Chuang (1966), and Faltinsen (1999) but their theories were limited to simple geometries. These models are also unable to simulate realistic hull details like appendages, or to simulate complex fluid–structure interactions which occur when the vessel is operating.

The development of Computational Fluid Dynamics (CFD) has resulted in the availability of tools that allow the simulation of slamming events with increased detail and complexity of hull shape (Chaudhry et al., 2022). CFD modelling can be used to accurately model fluid–structure interactions that are especially important for assessing slamming loads on planing hulls with appendages such as spray rails. As the impact of hull with water is not always symmetric, so researchers also use water entry simulations of hull section at a heel angle to model asymmetric impact (Xie et al., 2023).

Spray rails are parts of the hull that extend longitudinally into the water and are usually attached to the hull surface to redirect spray and to give better ride comfort and visibility. They have been studied extensively for their effect on resistance and seakeeping. For example, Seo et al. (2016) reported an 11.3% decrease in vertical acceleration when spray rail was installed in a high-speed monohull. Castaldi et al. (2021) noted a 5% decrease in resistance in towing tank studies, while Lakatos et al. (2019) studied the effect of various spray rail configurations on resistance characteristics. Ebrahimi et al. (2024) conducted a CFD study of the effect of spray rail number, size and orientation on hydrodynamic resistance and trim.

Although spray rails have the potential to affect the slamming impact behavior of the vessel, this effect has not been thoroughly investigated yet in existing studies. Some recent investigations have started to fill this gap. Hasheminasab et al. (2023) conducted water entry tests with a catamaran section comprising spray rails and reported that spray rails could have the potential to lower accelerations and peak pressures in the wet deck area. However, these results are not directly applicable to monohull planing boats because of the different slamming conditions caused by the different hull dynamics and impact geometries.

2. Numerical Methodology.

This section provides a brief description of the computational model for the analysis of slamming behavior of a planing hull section during symmetric and asymmetric water entry. This analysis is carried out using ANSYS Fluent software, including free surface modeling, overset meshing, and six degrees of freedom (6DOF) motion to simulate the vertical movement of the water impact. The main objective is to investigate the effect of the spray rails and heel angle on slamming pressures and vertical accelerations at the time of water entry.

2.1. Governing equations.

The fluid flow is assumed to be incompressible, Newtonian and the unsteady Navier–Stokes equations are used to model it. Solved numerically by the finite volume method in the 2D domain. The governing equations consist of continuity equation:

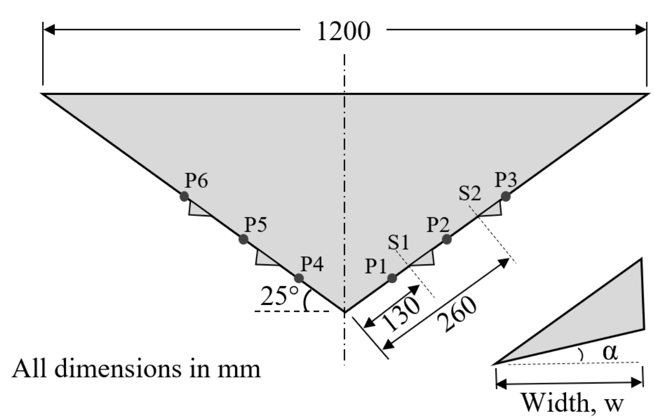
$$\nabla \cdot \mathbf{V} = 0 \tag{1}$$

and the momentum conservation equation:

$$\frac{d\mathbf{V}}{dt} = \mathbf{g} - \frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{V} \tag{2}$$

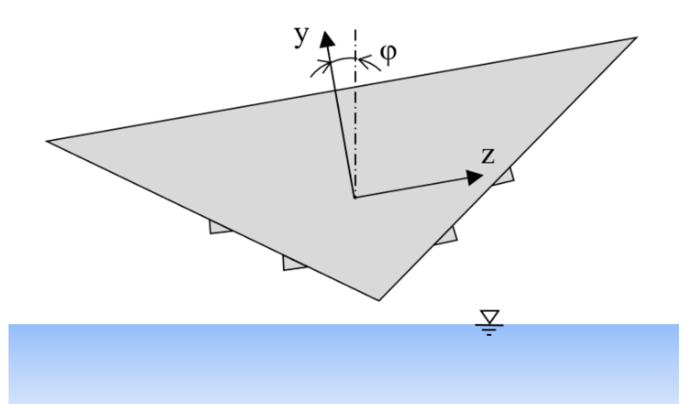
Where $\mathbf{V}$ is velocity vector, t is time, ρ is the density, p is pressure, and ν is kinematic viscosity of the fluid and $\mathbf{g}$ is gravitational acceleration. To resolve turbulence effects, the k-ω SST (Shear Stress Transport) model is adopted. This model combines the near-wall accuracy of the k-ω formulation with the free-stream robustness of the k-ε model, making it well-suited for capturing both boundary layer behavior and separated flow regions during high-speed water impact. The near-wall mesh is refined to maintain $y^+ < 100$, ensuring adequate resolution for wall shear and pressure gradients near the hull surface.

Figure 1: Model geometry.



Source: Authors.

Figure 2: Asymmetric entry angle.



Source: Authors.

The Volume of Fluid (VOF) method is used to capture the free surface between the water and air, requiring only a scalar volume fraction to track the free surface. This approach allows the prediction of interface deformation, spray formation and formation of air cavities during the transient slamming process to be accurately predicted. In this region, the mesh is refined to increase the resolution near the free surface to capture the pressure gradient and interface behavior accurately, the cells are reduced to 1/5 of the background mesh length.

2.2. Model geometry and test cases.

The hull section used in the analysis presented here is a two-dimensional (2D) wedge type planing hull which is a commonly used approximation in slamming studies as a good way to isolate the main hydrodynamic behavior during water entry. The wedge has a deadrise angle of 25°, and its geometry is consistent across all simulations. Spray rails are incorporated as sharp-edged longitudinal elements mounted symmetrically on both sides of the hull. The spray rails are positioned at vertical distances of 130 mm (S1) and 260 mm (S2) from the keel. The width w, of each spray rail is kept as 20 mm. The bottom surface of the rails is aligned horizontally with respect to the still water surface (i.e., rail angle $\alpha = 0°$). A schematic of the hull cross-section and spray rail placement is shown in Fig. 1. The pressures probes are placed at three locations P1, P2 and P3 on starboard, and three locations P4, P5 and P6 on port side. The distance between the probes is kept equal to 100 mm.

Table 1: Water entry cases.

Case	Entry Type	Heel Angle, φ
1	Symmetric	0°
2	Asymmetric	5°
3	Asymmetric	10°

Source: Authors.

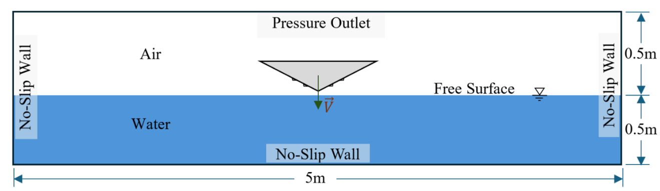
To investigate the effect of spray rails on slamming behaviour, the simulations are carried out using bare hull and hull appended with spray rails for symmetric water entry. To investigate the influence of heel angle on slamming response, three water entry cases are simulated, as summarized in Table 1. In each case, the same hull and spray rail configuration was used, while the initial orientation of the hull is varied to simulate symmetric (0° heel) and asymmetric (5° and 10° heel) water entry as illustrated in Fig. 2. The heel is applied as an initial angular offset prior to release, and the hull is allowed to translate vertically under gravity while other degrees of freedom are constrained. This configuration can be used to assess slamming loads and development of flow field for different entry angles, allowing for the separation of the effects of asymmetry.

This setup allows for an easy comparison of slamming pressures, acceleration response and flow characteristics for both the symmetric and inclined entries, which represents the effect of hull orientation on the performance of the spray rail and the effect of the slamming environment on the performance of the spray rail.

2.3. Domain and boundary conditions.

The simulation domain is designed to simulate the water entry of a planing hull into a two-phase air–water environment. The overall height of the domain is 1 m, and the width of the domain is 5 m. Water occupies the lower half, 0.5 m; the upper half, 0.5 m, is filled with air, and air is considered to occupy the initial free surface at mid-height. At the beginning of the simulation the hull model is positioned above the free surface and then falls and collides with the free surface due to gravity. The schematic of the domain under consideration and the boundary conditions are presented in Fig. 3.

Figure 3: Domain and boundary conditions.



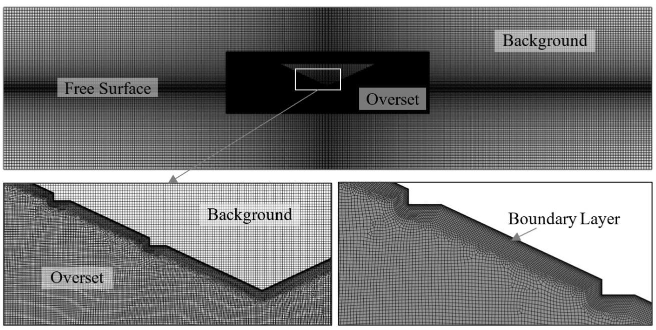
Source: Authors.

No-slip wall boundary conditions are applied to the hull surface and domain sidewalls. The top boundary is defined as a pressure outlet, allowing air to escape freely during upward spray formation. The bottom of the domain is also modeled as a no-slip wall. The water surface is initialized horizontally at a level beneath the hull to allow full observation of the free-fall and water impact sequence. The motion of the hull from drop point till reaching near the free surface is not solved to save computational time. Rather, the hull is initially positioned near the free surface and released under gravity. An initial downward velocity is applied on the hull model, calculated form the drop height of the hull. A six degree of freedom (6DOF) motion solver is employed, where only the vertical translation is permitted. All other degrees of freedom, including pitch, roll, and horizontal translation, are constrained to isolate vertical slamming behavior. The vertical motion follows the hydrodynamic forces on the hull during the impact, which enables the accurate simulation of the coupled fluid-structure interaction.

2.4. Meshing and temporal discretization.

An overset mesh approach is used to discretize the computational domain. The approach makes use of several overlapping grids, improving the flexibility and accuracy of the modelling. This overall configuration of the mesh, with the overset region, the background mesh and the interface between them, is depicted in Fig. 4. The outline of the hull is surrounded by a finely resolved overset region that overlaps with a coarser background mesh. The overset mesh has capability of independent motion, allowing detailed resolution of the dynamic water entry interface without the need for continuous re-meshing. Such a method can capture the complex flow interactions in the vicinity of the hull boundaries with high precision with low computational cost. Smooth transition zones are kept between overlapping meshes to assure numerical stability and consistency.

Figure 4: Model mesh with overset and background regions.

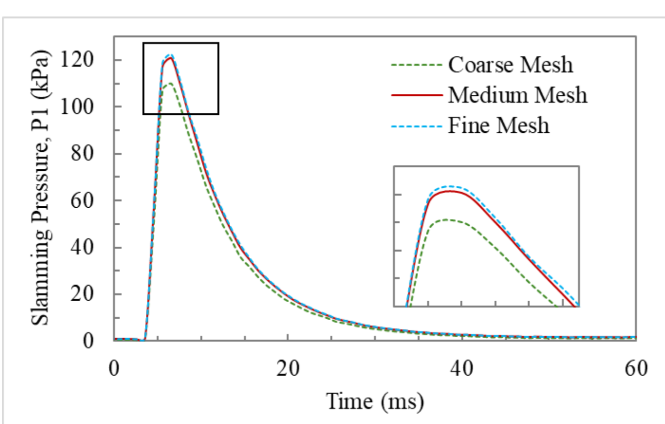


Source: Authors.

The time step is determined by an adaptive time step that is controlled by a Courant–Friedrichs–Lewy (CFL) number of 0.8 to guarantee numerical stability and temporal accuracy. The maximum time step is 0.0005 seconds, resulting in a time resolution of 2 kHz. This is enough resolution to record the high frequencies of pressure peaks and the abrupt changes in acceleration that are seen at impact.

A mesh convergence study is conducted using three mesh densities, as summarized in Table 2. The peak slamming pressure at probe location P1 was used as the primary convergence metric. Results in Fig. 5 illustrate that the coarse mesh underpredicts the pressure peak, while the fine and medium meshes yield closely matching results. The variation between the medium and fine meshes is minimal, indicating that further refinement has a negligible impact on the solution accuracy. Therefore, medium mesh is selected for all subsequent simulations to keep the computational cost low while ensuring sufficient numerical accuracy.

Figure 5: Mesh convergence study.



Source: Authors.

3. Experimental Validation.

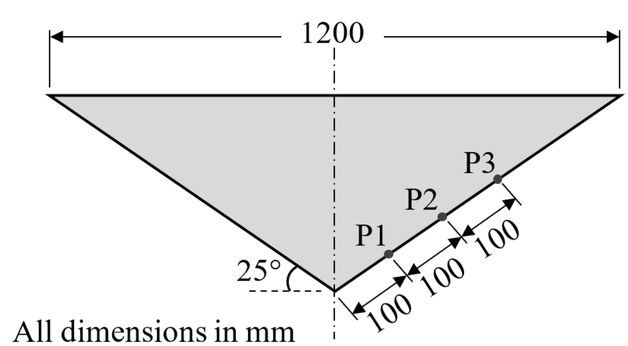
Table 2: Mesh convergence study.

Mesh Level	No. of Elements (Millions)	Peak Pressure at P1 (kPa)
Coarse	0.43	107.3
Medium	0.67	119.2
Fine	0.95	121.4

Source: Authors.

To ensure the reliability of the developed numerical model, validation is performed against the experimental results reported by Yettou et al. (2006) for the vertical water entry of a wedge-shaped body. The experimental setup consisted of a 30-meter-long, 2-meter-wide, and 2-meter-high tank, with a water depth maintained at 1 meter. The wedge model used in the experiment had a square cross-section of 1.2 m × 1.2 m at the top and a deadrise angle of 25°. The mass of the model was 94 kg, and the test case for wedge drop height of 1.3 m was used for validation. A schematic of the experimental model is shown in Fig. 6.

Figure 6: Wedge model used for validation from experiments of Yettou et al. (2006).



Source: Authors.

The evolution of the free surface during the water entry simulation is shown in Fig. 7, where the formation of spray and surface deformation patterns closely match experimental observations. Fig. 8 compares the numerical and experimental time histories of wedge displacement, velocity and acceleration. The results demonstrate good agreement, with the numerical model predicting the vertical motion within 6% error for displacement and 8% for velocity. The slight overestimation in velocity may be attributed to the absence of frictional losses in the numerical setup, which are naturally present in the experiments.

Figure 7: Free surface elevation during water entry simulation of the wedge section.

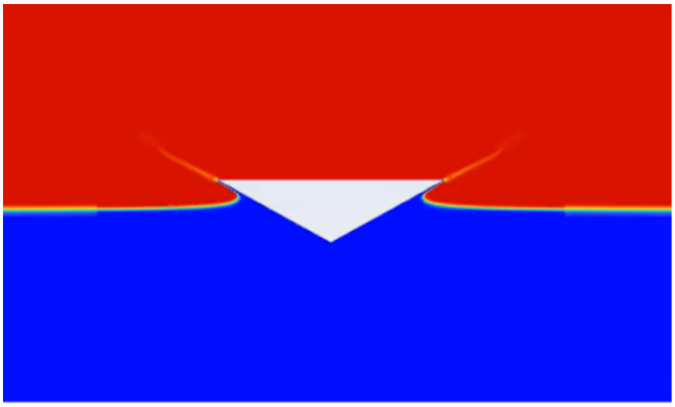


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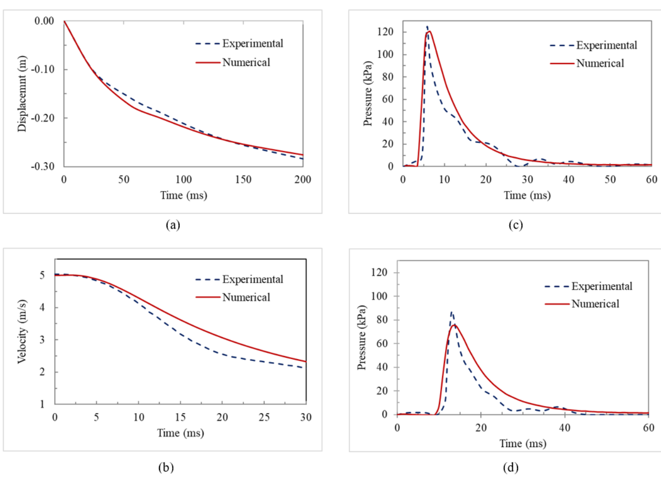
Figure 8: Numerical and experimental time history plots for (a) displacement, (b) velocity, (c) pressure at P1 and (d) pressure at P2.

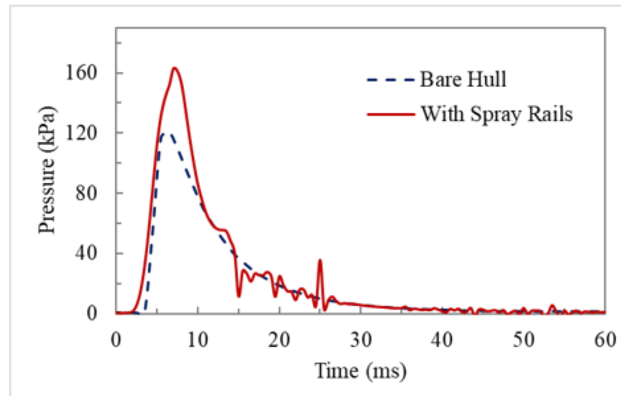


Source: Authors.

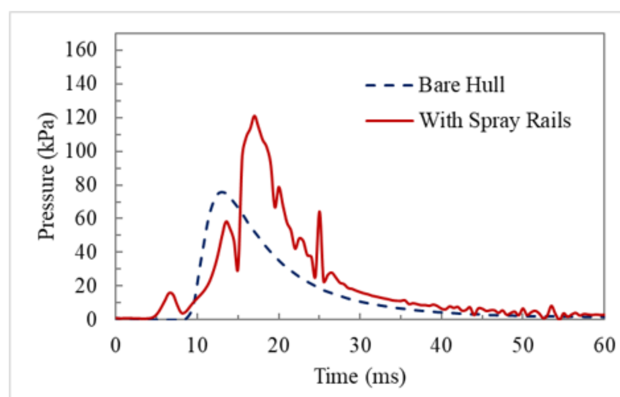
Slamming pressures are also computed from the CFD simulations at three different probe points. The probes are located along the wedge surface 100 mm apart from each other as shown in Fig. 6. The free surface elevation during water entry is shown in Fig. 7. The comparison of numerical pressure measurements with the experimental values is plotted in Fig. 8 for two locations, P1 and P2. The peak pressures predicted by the numerical model agree well with the experimental data, with a deviation of less than 10%. Furthermore, the predicted time of pressure curve peak value matches closely with the experimental results, indicating that the transient response is captured accurately. The experimental pressure decay is slightly more gradual, which may be due to the larger physical area of the pressure sensors compared to the localized numerical probes as also explained by Huang et al. (2021) in their analysis of lifeboat water entry.

Overall, the comparison is consistent with the ability of the CFD model to capture the important aspects of the water entry event including the free surface deformation, vertical motion, and localized pressures associated with the slamming event. These comparisons validate the CFD model and its application to the other parametric studies to follow. This validated model is thus used for all further simulations concerning spray rail effects when spraying with symmetric and asymmetric entry conditions.

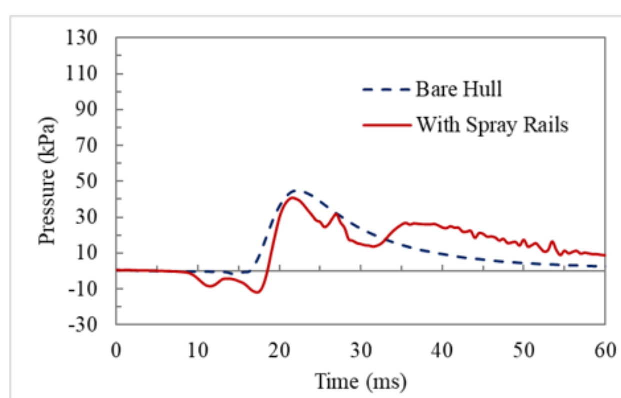
Figure 9: Slamming pressures for bare hull model and for hull appended with spray rails: (a) at locations P1 and P4, (b) at locations P2 and P5, (c) at locations P3 and P6.



(a) At location P1 and P4



(b) At location P2 and P5



(c) At location P3 and P6

Source: Authors.

4. Results and Discussion.

In this section the slamming pressure and acceleration time histories for all the test cases are given and discussed.

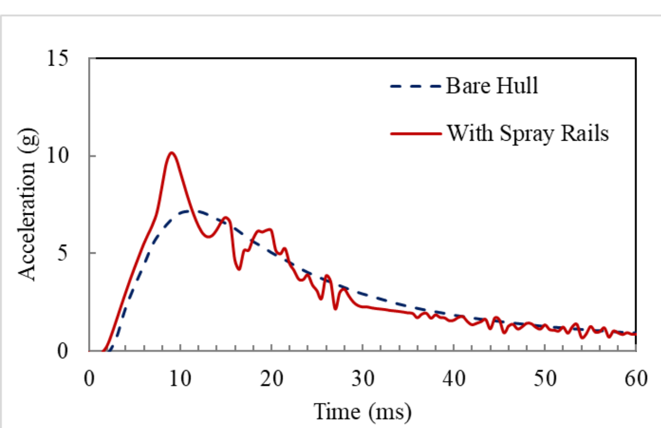
4.1. Comparison of slamming response with and without spray rails.

The results obtained from the bare hull (without spray rails) are compared with the spray-rail-equipped hull for the symmetric water entry case (Case 1), to evaluate the effect of the spray rails on the slamming phenomenon. The time history of the slamming pressures at various points (P1 to P6) on the hull surface is shown in Fig. 9. Due to the direct interaction between the upward flow and the lower spray rail (S1), peak pressure is greatly increased at P1, which is near the keel. This pressure spike is around 35%, which means that the loading to the pressure is increased at a localized level.

However, at the point further from the keel (i.e. P3) pressures are observed to fall slightly but the time of pressure rises. This has been attributed to the lateral deflection of spray in the presence of the rails which alters direction and concentration of the impacting fluid. Since the water entry is symmetric i.e. at zero heel, the pressure values at port P4 to P6 are equal to those at starboard P1 to P3. These observations indicate that spray rails can shift the pressure loading as well as cause an additional spatial variation in pressure intensity over the hull structure.

The dynamic response differences between these two configurations are further emphasized by the vertical acceleration time history of each configuration, as presented in Fig. 10. In the case of the hull with the spray rails, a sharp increase in acceleration is seen shortly after the water has come into contact with the rails, and there is a clear peak at t ~ 14 ms, where the flow impacts S1. A second fluctuation is noticed at flow S2. The overall increase for the first peak of acceleration is 38% higher than the bare hull, suggesting improved impulsive loading. The acceleration values are similar at later stages of entry, however, showing that most differences are obtained during the early impact phase.

Figure 10: Vertical acceleration for bare hull model and for hull appended with spray rails.



Source: Authors.

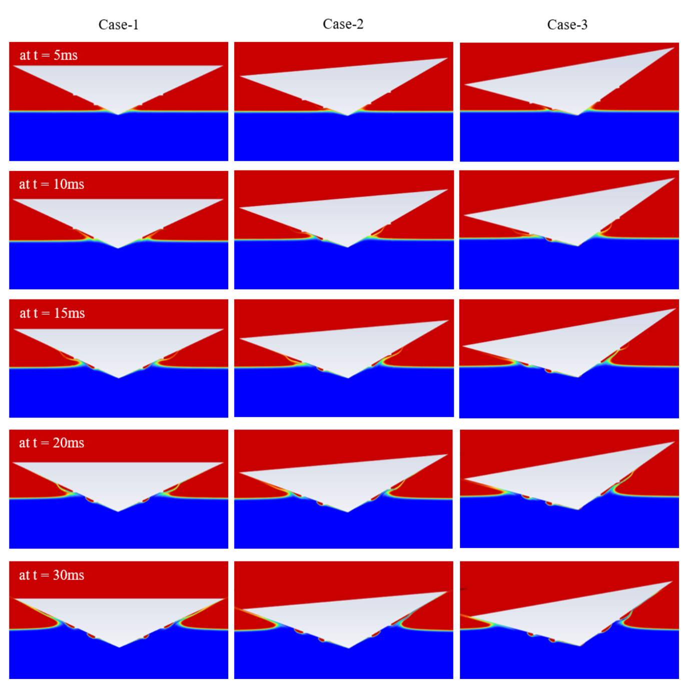
4.2. Effect of heel angle on slamming loads with spray rails.

To investigate the possible modification of slamming behavior by the inclined water entry, Cases 2 and 3 are performed with the same spray rail configuration, with inclined entry angles of 5° and 10°, respectively. These results are compared with the symmetric case (Case 1) in order to gain an understanding of the interaction between hull orientation and the presence of spray rails.

The free surface evolution during the water entry event for the three cases simulated is shown in Fig. 11. A spray sheet is created in the early stage of impact (5–10 ms) near the keel and moves up the hull surface in the direction of the jet. For the symmetric entry case, the spray is uniform on both sides, which implies that the impact of the fluid is balanced. Under asymmetric conditions the spray is more aggressive upward on the lower hull side and slows and weakens on the upper side.

The spray is deflected laterally from the spray flow as it collides with the spray rails. This deflection causes the spray sheet to stop smooth flow and creates an air gap between the spray and the hull surface above the spray rail. This cavity temporarily does not let water re-attach, changing the spray progression and the resulting pressure distribution. As the heel angle increases, the cavity effect will intensify because the flow will be more asymmetric and the separation of the spray is more extreme. In addition to altering the slamming pressures, these effects alter the vertical entry velocity and acceleration of the planing hull.

Figure 11: Free surface evolution during water entry at t = 5, 10, 15, 20 and 30 ms for Case 1, Case 2 and Case 3. (Panel order reconstructed from the original file sequence; verify against the source document before final submission.)

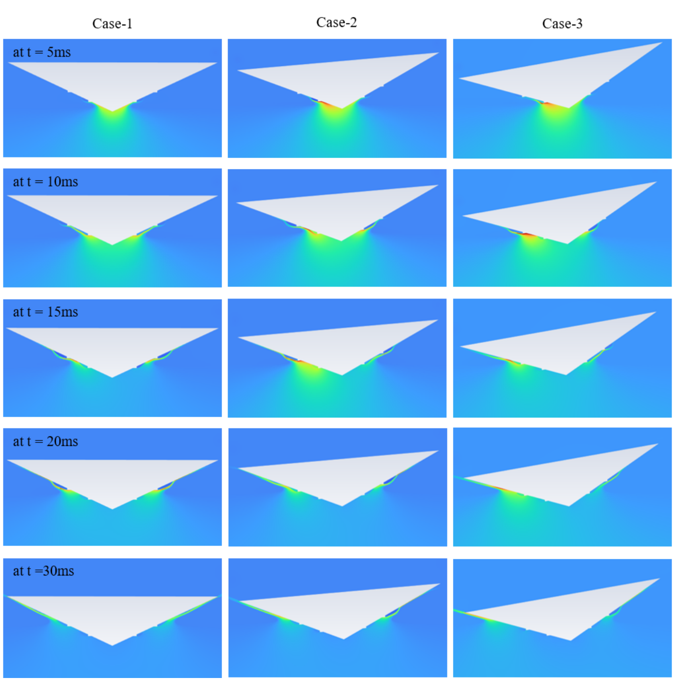


Source: Authors.

The change of pressure distribution around the fluid is illustrated in Fig. 12. In the symmetric case, the pressures are equally distributed throughout the hull, and the peaks begin near the keel and work outwards as the hull goes under. In the inclined cases, the pressure field becomes highly one-sided: the pressures increase significantly on the lower side of the hull where impact occurs sooner. Delayed and reduced pressure development on the upper side can be attributed to the protection provided by the hull inclination and the formation of the air cavity.

At later stages of the water entry, i.e. after 30 ms, the pressure front has moved beyond the region of interest i.e. the areas near keel where high impact pressures are experienced. The pressure distribution remains asymmetric. The inclined cases also have higher and more localized pressure areas on the lower side, and lower pressure development on the upper side due to the delayed contact of water and due to the separation of flow due to deflection of the spray. During this time, the air cavities above the spray rails remain, suggesting that spray does not reattach to the hull within the time observed. The results indicate that the combination of heel angle and spray rail interaction has a significant effect on the development of the slamming loads, and hence the pressure field is always asymmetric, which needs to be considered in the structural analysis and design of high speed planing hulls.

Figure 12: Pressure distribution evolution in the fluid domain at t = 5, 10, 15, 20 and 30 ms for Case 1, Case 2 and Case 3. (Panel order reconstructed from the original file sequence; verify against the source document before final submission.)

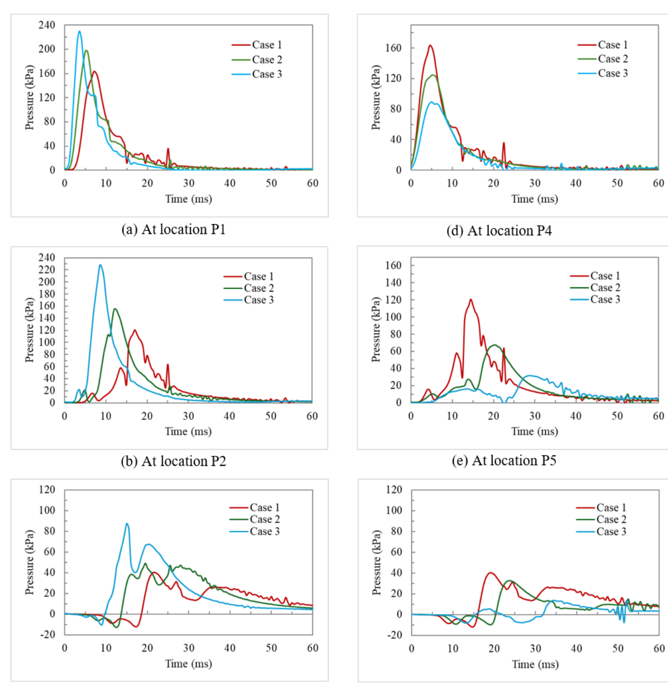


Source: Authors.

The slamming pressure time histories at all six pressure probe locations (P1–P6) for the planing hull with spray rails under symmetric and asymmetric water entry is presented in Fig. 13. At keel-adjacent probes (P1 and P4), the symmetric case exhibits a single dominant pressure peak, while in the inclined cases (φ = 5° and 10°), the lower side of the hull (P1) experiences an earlier and higher pressure peak due to earlier water contact. In contrast, the pressure at the opposite side (P4) is delayed and diminished, reflecting the deflected spray and delayed impact on the elevated hull surface. At pressure probes P1 and P4 which enter water before deflection of water by spray rails similar behaviour is observed as in the experiments of Barjasteh et al. (2016) for asymmetric water entry of wedges.

At locations P2 and P5, similar asymmetries are observed. The 10° heel case shows the most pronounced pressure differences between starboard and port sides, with P2 recording higher pressure for a longer duration compared to P5. This indicates that the greater the heel angle, the greater the imbalance in the pressure distribution. In addition, at the outermost probes (P3 and P6), the overall values of the peak pressure are lower but the difference between symmetric and asymmetric still remains. The results show the importance of the hull inclination in increasing the local slamming force on the one side of the vessel, which should be taken into consideration in the design of the hull and the fatigue analysis.

Figure 13: Slamming pressures for symmetric and asymmetric water entry of hull with spray rails: (a) at location P1, (b) at location P2, (c) at location P3, (d) at location P4, (e) at location P5, (f) at location P6.



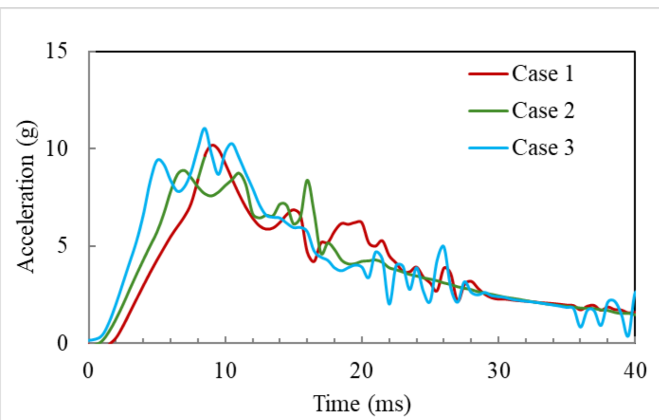
Source: Authors.

The vertical acceleration response of the hull for all three test cases is shown in Fig. 14. For the symmetric water entry (Case 1), the acceleration curve has two peaks: one from the impact of the water flow on the lower spray rail (S1) and the other from the impact of the water flow on the upper spray rail (S2). The response is symmetrical and balanced, with a fast increase and subsequent stabilization.

Vertical accelerations have more complex and irregular patterns in asymmetric cases. The initial acceleration peak occurs earlier and is higher in magnitude, particularly for the 10° heel case. This is attributed to the sudden fluid effect on the lower side. The second acceleration peak is not as pronounced though, because the water contact on the upper side is delayed, leading to a smoother less jarring impact. When considering the initial acceleration, the 10° heel case exhibits the highest acceleration, suggesting that the structure is subjected to a more severe impulsive loading when presented with an inclined entry.

As seen from these acceleration trends, the interaction with the spray rail and heel angle considerably influence the dynamic loading on the hull during slamming motion, which is consistent with the pressure results. The variation in acceleration behavior under asymmetric conditions can have implications for onboard equipment design and occupant safety.

Figure 14: Vertical acceleration for symmetric and asymmetric water entry of hull with spray rails.



Source: Authors.

Conclusions.

A numerical model was developed in this study to analyze slamming loads during water entry, which was based on a 2D CFD approach. The model featured overset meshing, a 6DOF solver for the dynamic motion and a Volume of Fluid (VOF) method to model the free surface. The model was validated by comparison with published experimental data, showing that the model is capable of accurately predicting slamming pressures and vertical accelerations during the water entry of the waterborne hull sections of a wedge shape. The model was then used to study the slamming response of a planing hull section with symmetric and asymmetric water entry when the spray rail is attached.

The results show that 2D CFD simulation can be used to satisfactorily reproduce the important slamming parameters of a water entry into a hull section, such as the effects of the hull appendages and the entry direction. The slamming pressure distribution completely changed with the introduction of spray rails; pressure magnitudes became as much as 35% higher at P1 and up to 45% higher at adjacent points such as P2. The results show that the theoretical model usually used for wedge impact is not sufficiently descriptive to model hull fluid–structure interaction when dealing with hulls that have spray rails, and that CFD models are better suited to such applications. Regarding acceleration response, spray rails resulted in a noticeable increase in the peak vertical acceleration, especially in the early impact phase. The first acceleration peak was measured to increase by 38%, mainly caused by the direct interaction of the spray directed upwards with the spray rail elements. These impulsive loads are important in the analysis of structural stresses and should be considered in the design of high-speed craft.

The evaluation of the asymmetric water entry also highlighted sensitivity of slamming behavior to heel angle. When the heel angle increased from 0° to 10°, the slamming pressure was distinctly asymmetric, with higher and earlier pressure peaks on the lower side of the hull and elevated peaks and delayed pressure loading on the other side of the hull. The asymmetry was paralleled by a similar change in acceleration profile, with inclined entries having more rapid and greater vertical acceleration at first impact. The results highlight the significance of the hull orientation on the severity of slamming and on the distribution of hydrodynamic loads. While the current study focused on a fixed spray rail configuration, further investigations are warranted to explore how variations in the number, width, and angle of spray rails affect the slamming characteristics of planing hulls. In addition, the hydroelastic response of hulls appended with spray rails remains an open area for future research.

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