CFD Study on Seakeeping Performance of Planing Hulls

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1 INTRODUCTION

The planing craft, a prevalent type of high-speed vessels, achieves high speed due to the additional hydrodynamic lift force, which reduces the wetted surface area and drag. Traditional approaches to evaluating its hydrodynamic performance rely heavily on model tests and empirical formulas, more likely resulting in high cost and limited accuracy. With advancements in high-performance computing and numerical techniques, computational fluid dynamics (CFD) has become an essential tool for addressing complex hydrodynamic problems at both research and industrial scales. This abstract presents a study on the seakeeping performance of a Generic Prismatic Plaining Hull (GPPH) using CFD. A scale model ($L = 2.414\text{m}$, $B = 0.6274\text{m}$) of GPPH, as shown in Fig. 1, was employed in the study.

Figure 1: GPPH geometry

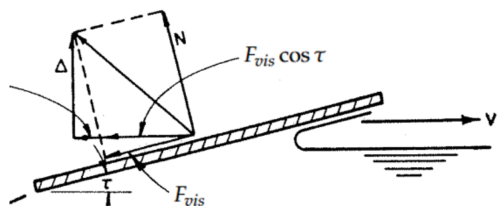


Figure 2: Force on a planing surface [1]

2 METHODOLOGY

This study aims to develop high-performance CFD-based models and validate the simulation results against benchmark and empirical data for the GPPH operating in calm water and head waves. To achieve this, both the empirical method based on the Savitsky formula [1–3] and CFD methods are utilized for computations.

2.1 Savitsky Method

The key concept of Savitsky method is to model the hull's behavior by balancing calm-water lift force and trim moment acting on it, accounting for hull geometry properties and test conditions. As illustrated in Fig. 2, the equilibrium system can be established as:

$$\begin{cases} \Delta F_z = F_L - F_{vis}\sin(\tau) + F_T\sin(\epsilon) - G \\ \Delta M_y = M_{y,0} + M_{y,p} + M_{y,f} + M_{y,T} \end{cases} \tag{1}$$

where F_L represents the hydrodynamic lift force, F_{vis} denotes the frictional force, τ is the trim angle, F_T and ϵ denote propeller thrust and its angle, respectively, and G represents gravity. $M_{y,0}$, $M_{y,p}$, $M_{y,f}$, and $M_{y,T}$ represent moment contributions from additional applied trim moment, pressure, friction, and thrust force, respectively.

To obtain the net lift force ΔF_z, the lift force ($F_L = C_{L\beta} \cdot 0.5\rho U^2 B$) of a planing hull with a deadrise angle β is determined using the lift coefficient $C_{L\beta}$, which is empirically formulated using Eq. (2). The frictional force ($F_{vis} = (C_F + \Delta C_F) \cdot 0.5\rho U^2 S_0$) is calculated using the ITTC formula, incorporating an added frictional coefficient ΔC_F to account for roughness, as shown in Eq. (3). The propeller thrust F_T is obtained by balancing the longitudinal force using Eq. (4).

$$C_{L\beta} = C_{L0} - 0.0065\beta C_{L0}^{0.6} \text{ with } C_{L0} = \tau^{1.1}\left(0.012\lambda^{0.5} + \frac{0.0055\lambda^{2.5}}{C_v^2}\right) \tag{2}$$

$$C_F = 0.075/(\log_{10}(Re)-2)^2 \text{ and } 1000\Delta C_F = 44\left(\left(\frac{\mathrm{AHR}}{L}\right)^{1/3} - 10Re^{-1/3}\right) + 0.125 \tag{3}$$

$$F_T = (F_L \tan(\tau) + F_{vis}\cos\tau)/\cos(\epsilon) \tag{4}$$

where C_{L0} represents the empirical lift coefficient of a zero-deadrise angle planing hull, λ denotes the mean wetted-length-to-beam ratio, $C_v = U/\sqrt{gB}$ is the beam-based Froude number, and AHR denotes the average hull roughness.
For the net trim moment ΔM_y, the centers of pressure and frictional forces must first be determined. The longitudinal center of pressure force l_p (measured from the transom) is empirically modeled using Eq. (5). The center of frictional force center, $l_f = 0.5B\tan\tau$, is assumed to be the geometric center of the wetted surface. Consequently, the moment contributions from pressure, friction, and thrust forces can be calculated using Eqs. (6) to (8), respectively.

$$l_p = C_p \lambda B \text{ with } C_p = 0.75 - \frac{1}{5.21(C_v/\lambda)^2 + 2.37} \tag{5}$$

$$M_{y,p} = F_L(LCG - l_p)/\cos(\tau) \tag{6}$$

$$M_{y,f} = F_{vis}\left(VCG - l_f\right) \tag{7}$$

$$M_{y,T} = F_T \sin(\epsilon)(LCG - LCP) - F_T\cos(\epsilon)(VCG - VCP) \tag{8}$$

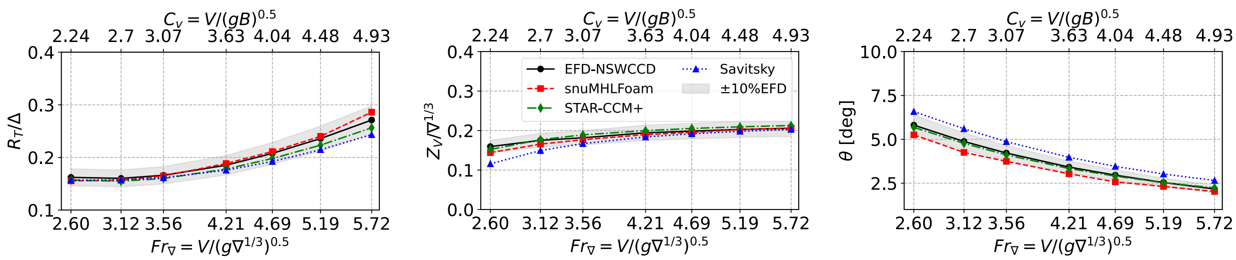
where LCG and VCG are the longitudinal and vertical centers of gravity, LCP and VCP are the longitudinal and vertical locations of propeller thrust.

2.2 CFD Method

The commercial software package STAR-CCM+ and the OpenFOAM-based solver, snuMHLFoam, developed by the Marine Hydrodynamics Laboratory at Seoul National University, are both employed in this study. The governing equations are the unsteady Reynolds-Averaged Navier-Stokes (uRANS) equations, coupled with the k-ω SST turbulence model. The Volume of Fluid (VoF) method is utilized for multiphase flow modeling. Computational settings for both solvers generally adhere to the ITTC guidelines [4], with adjustments to domain size and mesh resolution based on sensitivity tests to accommodate the high-speed operation of the planing hull. Additionally, a High-Resolution Interface Capturing (HRIC) is used in STAR-CCM+. Verification results of the current numerical models are not included in this abstract. Further details on the in-house solver snuMHLFoam and its seakeeping applications can be found in [5].

3 RESULTS

Calm-water tests were conducted over a wide range of hull speeds, with the results for hull drag, sinkage, and trim summarized in Fig. 3. The beam-based and displacement-based Froude numbers are shown on the top and bottom axes, respectively. All numerical methods demonstrate overall good agreement with experimental data [6]. As hull speed increases, a slight increase in sinkage and a reduction in trim (positive values indicating bow-up) are observed. Consequently, the wetted surface area decreases, and the force center shifts closer to the transom, indicating that a greater portion of the hull weight is supported by the induced hydrodynamic lift force. Compared to STAR-CCM+, snuMHLFoam shows an over-prediction of hull resistance, primarily due to the more diffusive interface capturing scheme employed in its VoF method.



(a) Drag (b) Sinkage (c) Trim

Figure 3: Comparison of calm-water performance

For head-sea tests, a benchmark study was conducted under a wave condition with $\lambda/L = 2.85, H/\lambda = 1/52$ at a speed of $Fr_\nabla = 4.21$ ($Fr = 1.84$). Fig. 4 compares CFD results for heave, pitch, and bow acceleration with experimental data [7] (EFD force data were unavailable). Both solvers show reasonable agreement overall. The rapid rise in bow acceleration indicates slamming, making it challenging to predict peak pressures accurately in CFD. Similar to calm-water tests, discrepancies between the solvers stem mainly from the interface capturing scheme, with greater effects during violent free-surface conditions caused by slamming. Fig. 5 shows the pressure distribution at maximum bow acceleration, where OpenFOAM's ‘noisy’ free-surface capture alters the dynamic pressure, especially on the hull's aft part.

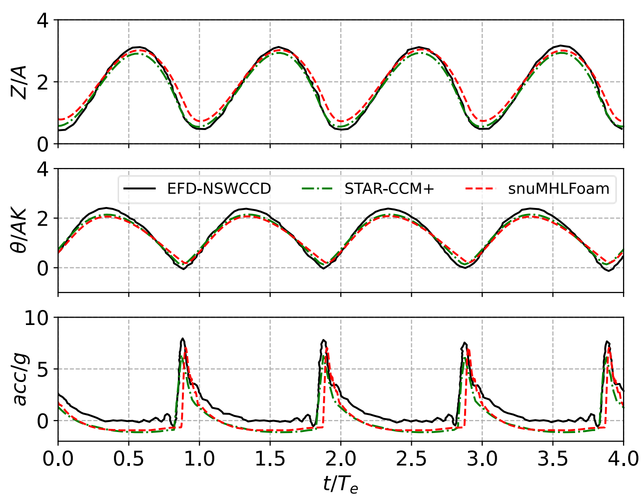


Figure 4: Benchmark study of seakeeping performance (Top to bottom: heave, pitch, and bow acceleration)

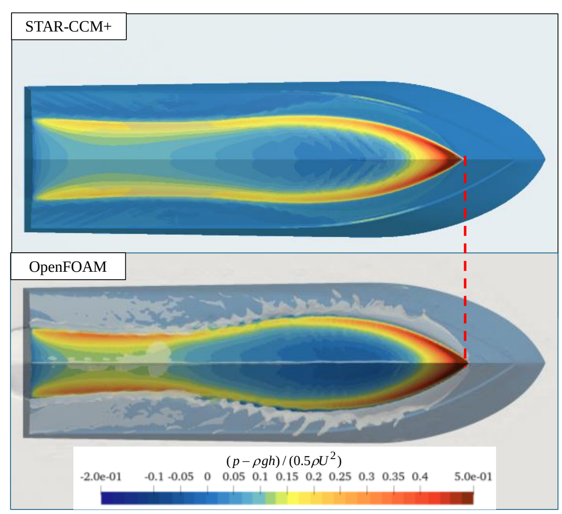
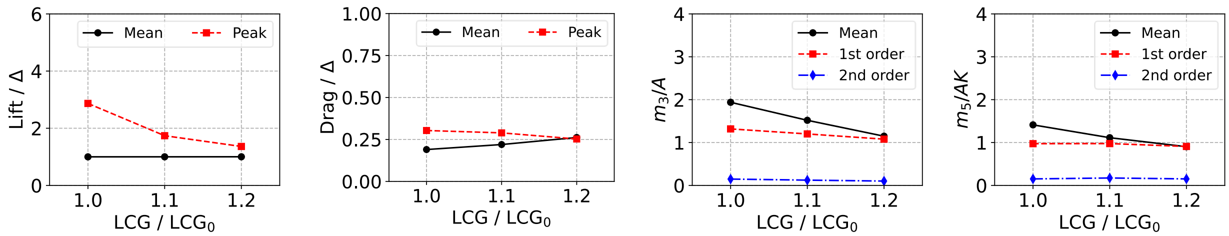


Figure 5: Pressure distribution on hull (Peak bow acceleration, bottom view)

Fig. 6 presents the sensitivity analysis of the longitudinal center of gravity (LCG), a critical parameter influencing trim angle and porpoising. The test conditions were identical to the head-sea benchmark study, except for LCG adjustments (10% and 20% forward from the original position LCG_0). Results include mean and peak forces (relative to the mean) and the mean, first-order, and second-order harmonic components of heave and pitch motions. The results indicate that shifting the LCG forward significantly reduces peak lift force, proving effective in mitigating slamming. This shift also decreases mean heave and pitch motions, which in turn increases the mean drag force.



(a) Lift (b) Drag (c) Heave (d) Pitch

Figure 6: Sensitivity test of longitudinal center of gravity (Solver: snuMHLFoam)

4 CONCLUSIONS

This study has studied seakeeping performance of a planing hull in calm-water and head-sea conditions using CFD. The following conclusions are drawn:

- Both CFD models demonstrated reasonable accuracy in predicting the hydrodynamic performance of planing hulls in calm-water and head-sea conditions.
- The interface capturing scheme is the primary source of discrepancies between the results from STAR-CCM+ and the OpenFOAM solver.
- Adjusting the LCG can significantly reduce peak lift force, making it a critical parameter for mitigating slamming.

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