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Experimental and Numerical Prediction of the Hydrodynamic Performances of a 65 ft Planing Hull in Calm Water

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Abstract. An extensive campaign of model and full scale experimental tests and numerical computations is being undertaken within the framework of the Project "SOPHYA - Seakeeping Of Planing Hull YAchts", co-financed by Friuli-Venezia Giulia Region in the field of joint industrial and academic research. The project is aimed at the prediction and optimization of the hydrodynamic performances of a 65 ft motoryacht by MonteCarlo Yachts SpA in calm water and in waves. In this paper, selected results of the numerical computations for the calm water case, conducted jointly by HyMO*Lab*-University of Trieste and by the University of Zagreb, are presented. RANS, Volume-of-Fluid and Level Set simulations are carried out in combination with an automatic mesh-generation tool, developed in this project within the OpenFOAM/foam–extend frameworks. The numerical results are compared with experimental data obtained within the project at the towing tank of the University of Naples.

Keywords. Planing hull, free-surface viscous-flow simulations, experimental tests

1. Introduction

This paper describes part of the scientific activities conducted so far in the frame of the Project SOPHYA. The study of the hull characteristics, in terms of comfort, seakindliness and powering, is being undertaken by means of experimental tests and numerical simulations. Measurements are carried out both in model and in full scale. In the latter, ship motions and powering are measured together with the actual sea state with an on-site dedicated wave buoy. The hull shape is then varied within commercial and operational limits, in the frame of a parametric investigation based on Free Form Deformation techniques and Reduced Models.

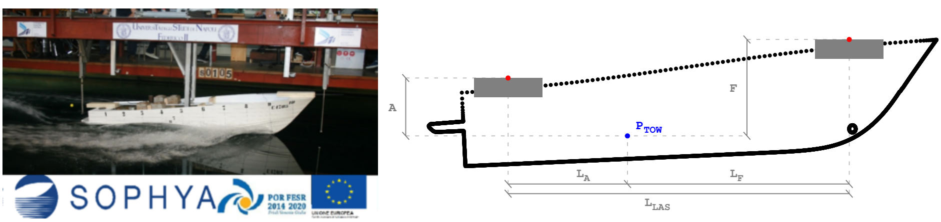
This work outlines some of the results related to the calm water hull performances in towing mode. The model scale experimental tests conducted at the towing tank of the

University of Naples-Federico II are presented. The numerical simulation framework developed jointly by HyMO*Lab*-University of Trieste and the University of Zagreb is then described and thoroughly discussed. In particular an automatic mesh-generation tool developed within the OpenFOAM/foam–extend framework, is presented. Issues related to numerical ventilation, observed in the results of the numerical simulations, are discussed according to the results of both Volume of Fluid (VoF) and Level Set (LS) interface capturing methods.

2. Brief Description of the Experimental Set-up

The calm water resistance tests (Fig. 1a) were performed in the experimental facility of the University of Naples-Federico II [1,2,3]. The main dimensions of the towing tank are $135\,m \times 9\,m$. The water is $4.2\,m$ deep. The maximum towing carriage speed is $8\,m/s$.

Before performing the experimental campaign, the 1:6.5 MCY model was trimmed to the required weight, longitudinal (LCG) and vertical (VCG) position of the centre of gravity and gyration radii.



(a) (b)

Figure 1. Experimental set up for the calm water resistance tests.

With reference to Fig. 1b, the model was towed at constant speed, free to heave and pitch and restrained in the other DoF. It was connected to the towing carriage through a mechanical arm apt to measure the horizontal component of the hydrodynamic force only (resistance). Values of trim and sinkage were derived from the measurements of the vertical distances between two carriage-fixed points and two body-fixed plates, as shown schematically in Fig. 1b. These displacements were obtained using laser devices (model Keyance IL-600), fixed to the towing carriage, with vertical beam trajectories. The sampling rate adopted is 5000 Hz. Trim θ and sinkage ΔZ are computed as follows:

$$\theta = \arctan\left(\frac{(\Delta h_1 - \Delta h_2) - (F-A)(1/\cos\theta - 1/\cos\theta_0) + L\tan\theta_0}{L_{LAS}}\right) \tag{1}$$

$$\Delta Z = \Delta h_2 - A(1/\cos\theta - 1/\cos\theta_0) + L_A(\tan\theta - \tan\theta_0) \tag{2}$$

where Δh_1 and Δh_2 are the vertical displacements of the bow and stern plates, θ_0 is the static trim at rest and the other variables are related to the distances shown in Fig. 1b.

3. Processing of Experimental Data and Statistics

Time series of the experimental measurements were analyzed after manual windowing aimed at extracting stationary conditions only. Fig. 2 shows a typical outcome of a single test, after rearrangement of the sinkage/trim data according to eq. 1-2 above. In general, outliers of the time series are rejected using a 3σ threshold. Confidence intervals of experimental data are represented by *mean* $\pm 2\sigma$ or alternatively *min/max* values.

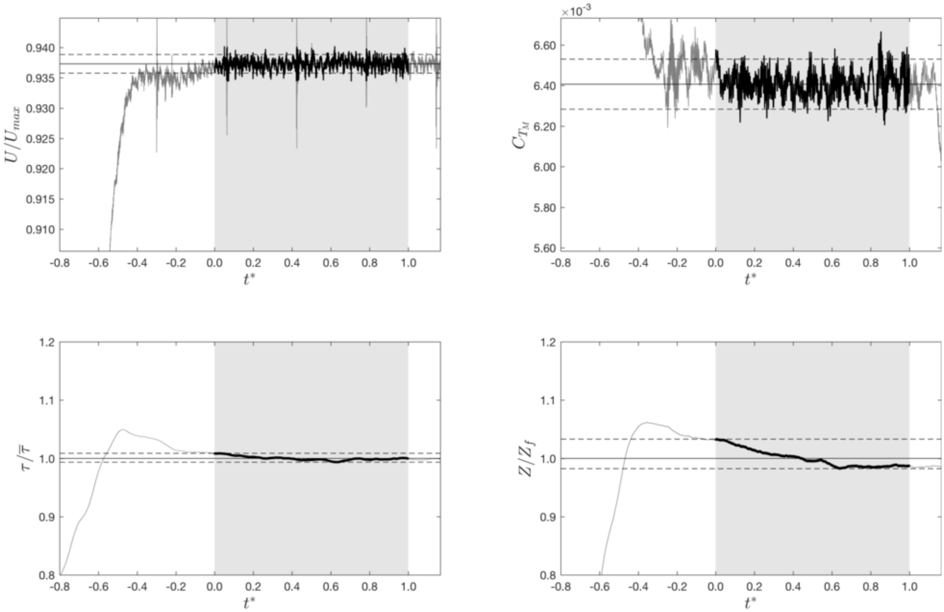


Figure 2. Sample time series of adimensional carriage speed (top-left), total resistance (top-right), trim (bottom left) and sinkage (bottom-right). Shaded interval: analysis window; solid black line: mean value; dashed black lines: confidence limits.

The carriage speed shows a fairly good signal with reduced noise. Isolated very high peaks are found here and there, possibly related to small discontinuities in the rails of the towing system. The hydrodynamic resistance of the hull does not present relevant outliers, so raw data have been used without filtering. Both trim and sinkage show reduced noise but with remarkable variations inside the time window where speed and resistance are assumed stationary. A monotonic behavior is typically observed in the time domain. In these cases, the confidence interval of the data is given by maximum and minimum values within the time window.

4. Numerical Simulations

4.1. Mathematical and Numerical Model

In this section governing equations and numerical details used for CFD calculations are presented. The equations are discretised using collocated Finite Volume (FV) method implemented within foam–extend open-source software. Software library called Naval Hydro Pack based on foam–extend is used, specialized for large-scale two-phase flows encountered in naval hydrodynamics.

A two-phase, incompressible, turbulent and viscous flow model is employed, governed by the continuity and Navier-Stokes equations:

$$\nabla\bullet\mathbf{u} = 0\,, \tag{3}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla\bullet((\mathbf{u} - \mathbf{u}_M)\,\mathbf{u}) - \nabla\bullet(\nu_e \nabla \mathbf{u}) = -\frac{1}{\rho}\nabla p_d\,, \tag{4}$$

where $\mathbf{u}$ stands for the velocity field, $\mathbf{u}_M$ is the grid velocity acconuting for the Space Conservation Law [4], ν_e is the effective kinematic viscosity allowing eddy viscosity turbulent modelling, and ρ stands for the discontinuous density field. p_d is the dynamic pressure calculated as: $p_d = p - \rho\mathbf{g}\bullet\mathbf{x}$, where $\mathbf{g}$ denotes the gravitational acceleration and $\mathbf{x}$ the radii vector. In order to properly resolve the discontinuity of density and dynamic pressure at the free surface, interface-corrected discretisation schemes based on the Ghost Fluid Method (GHF) are employed [5]. This approach removes the problem of spurious air velocities occurring in the air phase next to the interface.

The present GFM takes into account only the normal stress balance, while the tangential stress balance is approximated by blending the dynamic viscosity using the volume fraction variable α:

$$\nu = \alpha \nu_{water} + (1 - \alpha)\,\nu_{air}\,, \tag{5}$$

where ν presents the dynamic viscosity of the mixture, while ν_{water} and ν_{air} denote dynamic viscosities of water and air, respectively.

Two free surface capturing methods are used and compared in this work: the Volume of Fluid (VoF) method and the Level Set (LS) approach. In VoF method the volume fraction variable α is transported using the following equation:

$$\frac{\partial \alpha}{\partial t} + \nabla\bullet(\mathbf{u}\alpha) + \nabla\bullet(\mathbf{u}_r \alpha(1-\alpha)) = 0\,, \tag{6}$$

where the third term presents the interface compression using the compression velocity $\mathbf{u}_r$ following [6]. In the LS approach, implicit redistancing is used to maintain the sign distance characteristic of the field [7]:

$$\frac{\partial \Psi}{\partial t} + \nabla\bullet(\mathbf{c}\Psi) - \Psi\nabla\bullet\mathbf{c} - b\nabla\bullet(\nabla\Psi) = b\frac{\sqrt{2}}{\varepsilon}\tanh\left(\frac{\Psi}{\varepsilon\sqrt{2}}\right)\,, \tag{7}$$

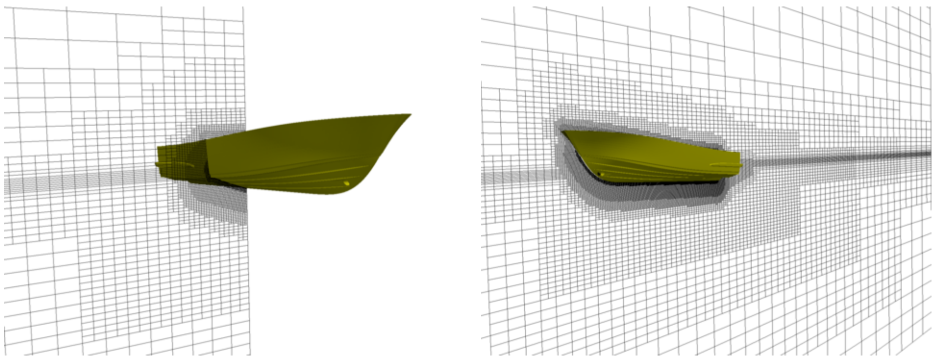
where Ψ stands for the Level Set field, while b and ε stand for diffusion coefficient and width parameter, respectively. $\mathbf{c}$ is the modified convective velocity. For further details regarding LS interface capturing method the reader is referred to Vukčević et al. [7].

For the simulations where dynamic sinkage and trim is calculated, a geometric method is used to integrate the rigid body motion equations [8]. Surge, sway, yaw and roll degrees of freedom are constrained using Lagrange multipliers.

The numerical model has proved accurate and robust and it has been employed in the recent past in variety of applications related to fluid-structure interaction, with or without free surface [9,10,11].

4.2. Automatic Grid Generation

Pursuing the industrial goals of the project SOPHYA, in particular those related to the reduction of the pre-processing time-to-simulation, an automatic grid generation procedure has been developed and tested. The procedure is based on open-source tools available in the OpenFOAM library. Octree non-isotropic meshes, with wall layer cells of prescribed thickness, are generated. The generation is based on very simple inputs, i.e. ship length, attitude, speed and transverse size of the basin. The grid resolution, and consequently the number of cells, is set using few simple non-dimensional parameters that depend on y^+ and Froude number. Fig. 3 shows a sample case.



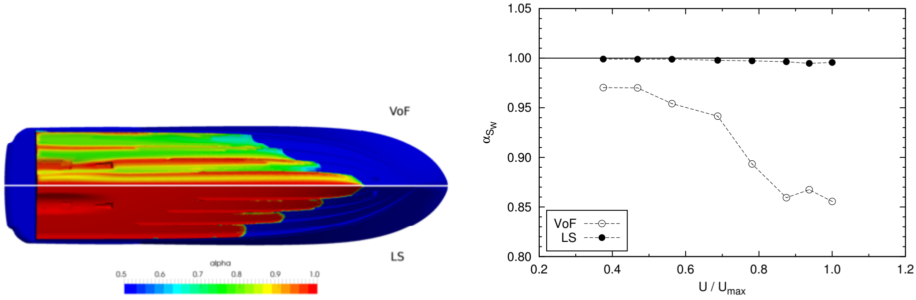
(a) (b)

Figure 3. Sample grid obtained with the home-developed automatic mesh generation procedure.

5. Results

It is well known from the literature that numerical ventilation (NV) issues may be encountered in VoF-based numerical simulations of planning yacht hydrodynamics. NV manifests itself when volume fraction smearing is transported along the whole wetted hull, leading (among other effects) to lower viscous stresses [12]. In order to limit this effect, different approches [13] have been adopted, among others, the artificial suppression method is the most used. This method consists basically in adding a negative source term to the volume fraction transport equation if the volume fraction is above 0.5 and the wall distance is lower than a prescribed distance. Other methods tackle the problem using a different advection scheme, such as modified HRIC [14]. This method aims at reducing volume fraction smearing at the interface, limiting the inception of NV. The way in which the NV, occurring in the VoF method, influences the results is the following: since the dynamic viscosity is calculated using Eq. 5, the mixture viscosity on a considerable portion of the wetted surface is significantly lower than the actual viscosity of water.

In the following, the preliminary results obtained by means of the two different interface capturing methods described in Section 4, namely VoF and LS, are discussed. No artificial suppression is applied. The investigation is carried out in model scale. Fixed sinkage and trim conditions are enforced, corresponding to the position of the hull, as measured in model scale experiments.

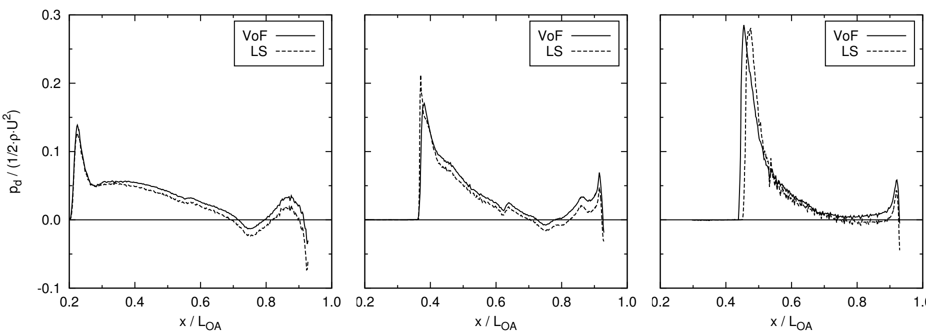


(a) (b)

Figure 4. (a) Bottom view of the volume fraction on the wetted hull surface using VoF (upper) and LS (lower) at the highest design speed. (b) Volume fraction on the wetted hull surface, both with VoF (○) and LS (•), as function of hull speed.

Fig. 4a shows the volume fraction on the wetted hull surface. The geometry of the wetted surface at the bow is significantly different: in LS simulation, the wetted surface exhibits a step-like behaviour caused by spray-rails, while the smearing of the VoF field partially diminishes the effect of the spray-rails, increasing the overall wetted surface. In Fig. 4b the effect of hull speed on *NV* is highlighted. The benefits of using LS method are clearly visible, especially at high speed.

Consequences of *NV* are clearly observed on the pressure distribution along the hull. Fig. 5 shows the non-dimensional dynamic pressure along three longitudinal cuts on the hull surface for both VoF and LS simulations. Moving from the bow towards the stern, an increasing difference between VoF and the LS pressure is found. The smaller viscosity due to *NV* in VoF causes smaller pressure drop along the hull, compared to the LS case. As a consequence of VoF field smearing at the bow, the pressure peak in Fig. 5b is also smeared, while the peak in Fig. 5c is shifted towards the bow.



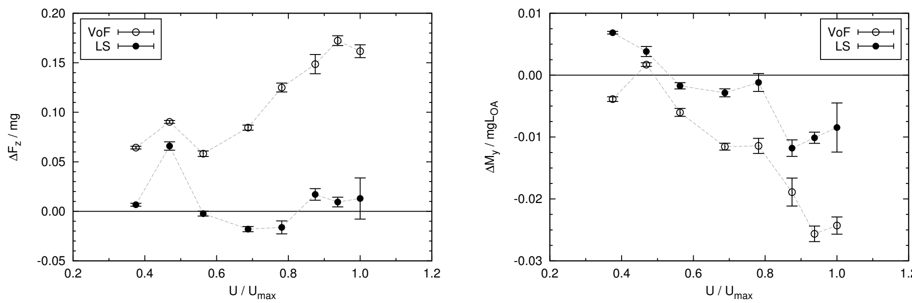
(a) (b) (c)

Figure 5. Non-dimensional dynamic pressure along three longitudinal cuts (10% (a), 50% (b) and 80% (c) of the hull half-width) on the hull surface at the highest design speed. Solid line: VoF; dashed line: LS.

The smaller pressure drop in turn influences the integral vertical pressure force and the pitching moment, as shown in Fig. 6. The Figure shows the non-dimensional error in the vertical force and in the pitching moment with respect to the towing point.

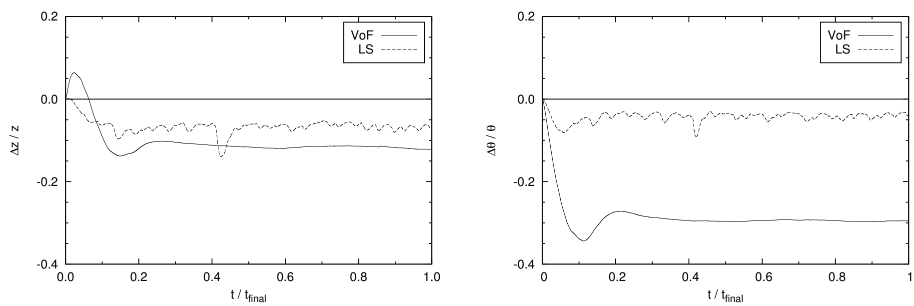
Hence, since the geometry of the interface-hull intersection is of paramount importance for the performance of planning crafts, LS method presents a better option for interface capturing.

Finally, the consequences of *NV* on the pressure distribution along the hull, can be easily observed in free trim and sinkage simulations. Fig. 7 shows the time series of the non-dimensional sinkage (a) and trim (b) during the 2-DoF simulation (VoF and LS) at the highest design speed. The largest differences between VoF and LS are found in the trim angle.



(a) (b)

Figure 6. Non-dimensional error in the vertical force (a) and in the pitching moment (b) with respect to the towing point. VoF (○) and LS (•) simulations.



(a) (b)

Figure 7. Time series of the non-dimensional sinkage (a) and trim (b) during the simulation at the highest design speed. Solid line: VoF; dashed line: LS.

6. Conclusions

In this work, some of the results of the ongoing joint industrial/academic Project “SOPHYA - Seakeeping Of Planing Hull YAchts” have been presented. In particular, selected results of the RANS simulations in calm water, conducted jointly by HyMO*Lab*-University of Trieste and by the University of Zagreb, are presented.

An automatic grid generation procedure has been developed. A significant reduction of the pre-processing time-to-simulation, along with higher mesh quality, has been achieved.

The well known problem of numerical ventilation (*NV*) has been investigated. The *NV* phenomenon, clearly visible using the Volume-of-Fluid interface capturing method, has been largely reduced adopting the Level Set method. Significant reduction in residual force and moment have been also achieved.

The use of meshes with a relatively low number of cells, along with a fast solver within the Naval Hydro Pack library, allowed to obtain results in a much shorter time compared to standard two-phases open-source solvers.

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