APPLICATION OF CFD CALCULATIONS FOR THE IMPROVEMENT OF PLANING CRAFTS MANOEUVRABILITY MATHEMATICAL MODELS

D.Villa, M.Viviani, E.Ferri
Department of Electrical, Electronic, Telecommunication Engineering and Naval Architecture
(DITEN), Naval Architecture and Marine Engineering Group, University of Genoa
Via Montallegro 1, 16145 Genova, Italy
diego.villa@unige.it, michele.viviani@unige.it, elena_ferri@outlook.it

Please underline the name of the co-author who will present the paper at the conference

ABSTRACT: The present paper deals with the manoeuvrability of planing crafts. A previously developed mathematical model for the prediction of the 4+2 DOF boat motions is considered and direct CFD results for the evaluation of manoeuvring coefficients are used, substituting the values obtained from regression formulae. Results are validated at first against captive model tests measurements, then simulations of full scale sea trials are presented, showing promising results which allow to consider the proposed approach feasible for the prediction of planning boats manoeuvrability.

INTRODUCTION

The high performance requirements for propulsion systems and the increasing attention on manoeuvring features, suggest the need for a thorough investigation about planing hull dynamics, already in the preliminary stages of the boat design. Despite during years a rather large number of studies has been carried out on the topic of planing hull dynamics, very limited data may be found in literature about planing hulls manoeuvrability [1][2]. As a matter of fact, most of studies have been concentrated on the topic of resistance prediction and boat powering, with some attention also on dynamic stability and seakeeping.

Considering this, in previous activities a time domain simulator, developed in Matlab-Simulink environment, has been developed at the University of Genoa, at first [3] adopting the 3+3 DOF approach proposed in [1]; in this approach, however, running attitude of the boat is given as a function of the drift angle only, partially preventing the possibility to consider its effect on the manoeuvrability characteristics of the boat. In a successive work [4], therefore, data from [2] have been used in order to extend the model to 4 DOF (adding roll to the usual motions in the horizontal plane) completely interacting with each other and to take into account the effect of trim and rise; results obtained showed a good agreement between numerical calculations and sea trials results. In the “Previous Activities” section, a brief overview of the proposed approach is reported.

Despite the promising results, discrepancies still exists; moreover, the available database of experimental data in literature [2] is only limited to prismatic hulls, thus not considering the effect of more complex shapes. Having this in mind, in the present work a series of direct numerical calculations adopting a commercial RANS code have been carried out, with the aim of investigating the possibility of obtaining part of the data needed for the model, in order to avoid the necessity of previous experimental data and to have the possibility of dealing with different hull shapes. The adopted approach is presented in the “CFD Approach” section. Moreover, in the same section some results are presented. At first a comparison with experimental data of static drift tests [1] is reported. Then, the procedure is directly applied to the same test case considered in [4], for which results of full scale sea trials are available; the resultant simulations are reported, comparing with those previously obtained. Results of this series of calculations are presented and discussed, allowing to get an insight into the problem and to track the way for the development of a fully numerical model for planing boats manoeuvrability.

PREVIOUS ACTIVITIES

4+2 DOF Planing boat manoeuvrability simulator

The 4+2 DOF manoeuvrability simulator developed in [4] is capable of evaluating the boat behaviour during manoeuvres, including the mutual interaction among all the elements involved, including obviously ship hull, propulsors and governor, plus the complete propulsion system and simplified automation. A schematic overview of the simulator is reported in Figure 1.

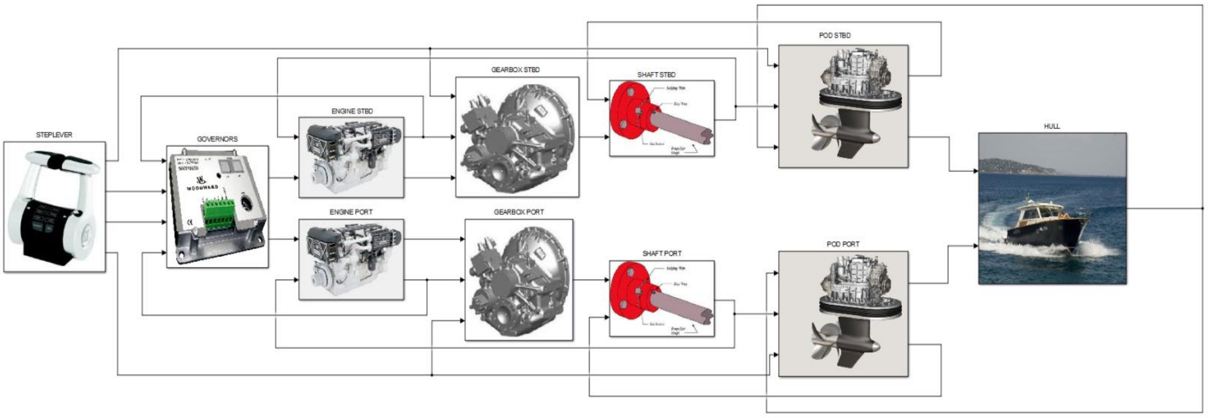

Figure 1- Simulator structure

In the present paper, attention is focused on the manoeuvrability part of the simulator, with particular attention on the hull forces. As a consequence, only these parts will be described in depth, while more details on the complete simulator are omitted for the sake of shortness and they may be found in [4].

As usual when dealing with the manoeuvrability problem, two reference frames are adopted, one fixed relative to the Earth $[O_0, x_0, y_0, z_0]$ and another fixed relative to the ship $[O, x, y, z]$, as shown in Figure 2. In the present case, it has been decided to adopt a moving frame which follows the boat motion in the horizontal plane, keeping the z axis always vertical (with the ship rolling around the longitudinal axis). The longitudinal (x) position of the origin O is located in this case around the 40% of total length, starting from transom; the y position coincides with the ship midline and the vertical (z) position is located at the same height as the centre of gravity .

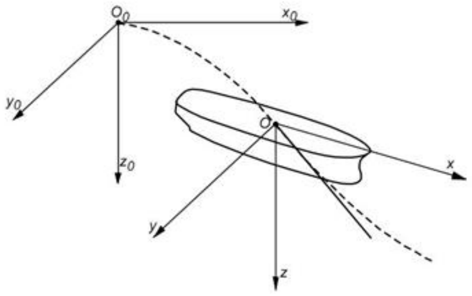

Figure 2 – Reference frames

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As mentioned, the simulator deals with 4 DOF (the usual 3 DOF in the horizontal plane plus roll). Heave and pitch motions are only considered as dependent on the drift angle of the boat, in accordance to the approach proposed in [1]. The equations adopted are reported in (1).

$$\begin{cases} \mathbf{m_x \dot{u} + M(-vr - x_G r^2 + z_G pr) = X_H + X_P + X_{POD}} \\ \mathbf{m_y \dot{v} + M(ur + x_G \dot{r} - z_G \dot{p}) - Y_{\dot{r}} \dot{r} = Y_H + Y_P + Y_{POD}} \\ \mathbf{I_x \dot{p} - I_{xz} \dot{r} - M z_G (\dot{v} + ur) - K_{\dot{p}} \dot{p} = K_H + K_P + K_{POD}} \\ \mathbf{I_z \dot{r} - I_{zx} \dot{p} + M x_G (\dot{v} + ur) - N_{\dot{v}} \dot{v} = N_H + N_P + N_{POD}} \end{cases} \tag{1}$$

Where: M is the ship mass, $I_{\square\square}$ are the inertial terms; x_G, y_G, z_G denote the centre of gravity position; u, v, p and r are the surge, sway, roll and yaw velocity, respectively; $m_x = M - X_{\dot{u}}$, $m_y = M - Y_{\dot{v}}$, $I_x = I_{XX} - K_{\dot{p}}$, $I_z = I_{ZZ} - N_{\dot{r}}$, X, Y, N and K are longitudinal and lateral forces and yaw and roll moments acting on the boat, with subscript H, P and POD representing hull, propeller and pod respectively.

The hull forces and moments are given as a function of advance speed, drift angle, heel angle and yaw speed. In particular, two separate effects are defined, following (at least partially) the approach proposed in [1]. At first, the following non-dimensional coefficients for hull forces and moments are defined:

$$\boldsymbol{C_{Fx} = \frac{X_H}{0.5\, S_y\, \rho\, U^2}} \qquad \boldsymbol{C_{Fy} = \frac{Y_H}{0.5\, S_y\, \rho\, U^2}}$$
$$\boldsymbol{C_{Mz} = \frac{N_H}{0.5\, S_y\, \rho\, L_{OA}\, U^2}} \qquad \boldsymbol{C_{Mx} = \frac{K_H}{0.5\, S_y\, \rho\, L_{OA}\, U^2}} \tag{2}$$

Where L_{OA} is the overall length, S_y is the area of the longitudinal section of the hull (considered at rest), ρ is the water density and U is the model speed. The values of the coefficients are given as a function of drift angle β, Froude number F_N and heel angle φ.

In addition, forces and moments due to yaw rate are depending on yaw rate itself, Froude number and running attitude (trim and rise), as follows:

$$\begin{aligned} \boldsymbol{F_{y(r)}} &= \boldsymbol{Y_r(r, F_N, \tau, Z)r} \\ \boldsymbol{M_{z(r)}} &= \boldsymbol{N_r(r, F_N, \tau, Z)r} \end{aligned} \tag{3}$$

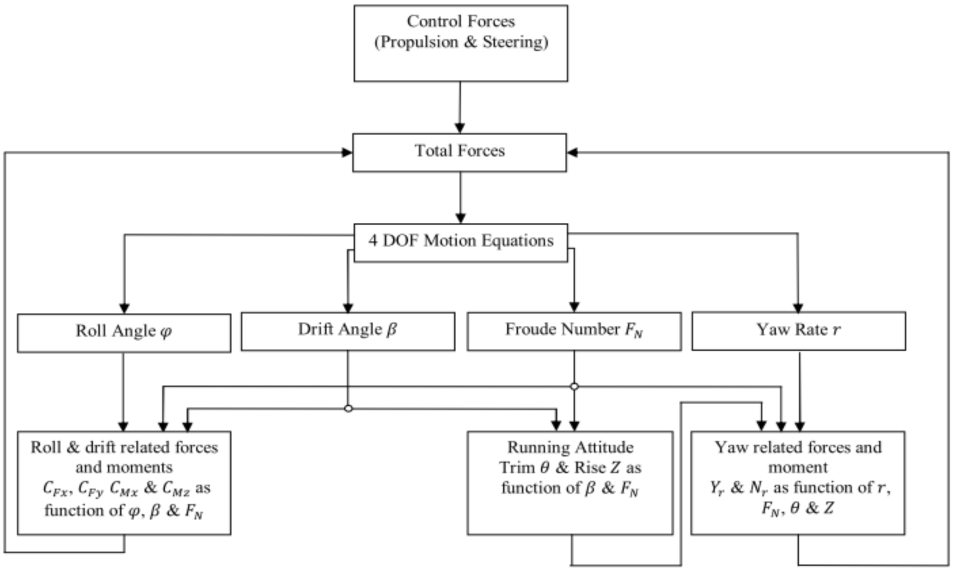


Figure 3- 4DOF model

Trim and rise, in their turn, are evaluated step by step as a function of the drift angle. A schematic summary of the proposed approach is illustrated in Figure 3.

In [4], all the forces have been evaluated adopting the regression formulae proposed by Henry in [2] on the basis of the results of an experimental campaign on prismatic hulls.

Test case and selected results

The boat considered in [4] and used in the present work as the second test case (named "Podded" in the following) has the main characteristics reported in Table 1. It is a planing boat equipped with two azimuthal podded propulsors, having a maximum speed of about 32.5 kn. The body plan of the boat is reported in Figure 4.

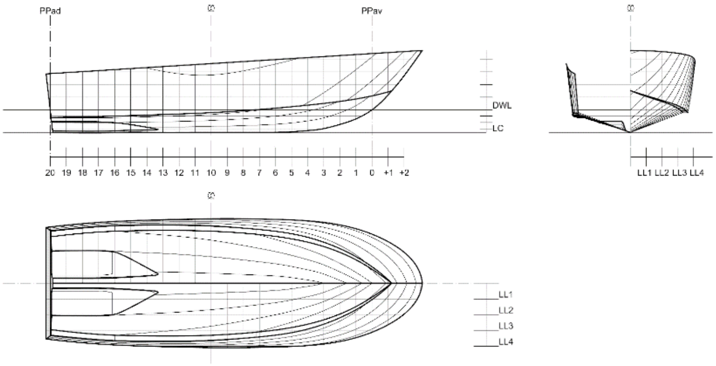


Figure 4 – "Podded" case: Construction plan

CHARACTERISTIC	VALUE
Length [m]	11.95
Beam [m]	4.095
Draft [m]	0.716
Wetted Surface [m^2]	6.38
Max Speed [kn]	32.5
Deadrise [°]	18°
Engine	2xFPT N67
Propulsor	2x ZF 2800

Table 1: Main data

In [4], simulation results obtained with the developed model have been reported and compared to full scale tests, showing a very promising correspondence. The results are reported in the following section "Test case 2 – "Podded" – CFD + SIMULATION" for the sake of shortness.

Despite the promising results obtained, some shortcomings of the proposed method clearly arose. In particular, data reported in [2] are referred only to prismatic hull forms, thus not considering the effect of some characteristics, such as variable deadrise angle, spray rails, double chine, etc. Moreover, the running attitude of the boat certainly affects the forces during the manoeuvre; in [4] the running attitude in straight motion has been evaluated by means of CFD and then the correspondent one during manoeuvre has been predicted considering Katayama results, in an engineering approach. This, however, has evident limitations. As a consequence, it has been decided to explore the possibility of substituting the experimental data of [2] with direct CFD calculations; this could allow to consider directly the real hull form and, moreover, to evaluate the running attitude in correspondence to the different running conditions (drift, heel, yaw). In the present work, attention has been focused on drift/heel cases only, leaving yaw for future activities. The results obtained are reported in the following section.

CFD / SIMULATION APPROACH

Test Case 1 – TB45 – validation of CFD approach

With the increase of the computational capabilities, the implementation of CFD methods to solve the flow field around complex objects has become nowadays a reliable tool. However, especially when dealing with new cases (such as the manoeuvrability of planning boats), the numerical calculations still need to be validated by means of experimental measurements. For the “Podded” test case of interest, however, no model tests were available. As a consequence, it was decided to consider some of the experimental results in model scale presented in [1]; in particular, the TB45 model (whose main characteristics and body plane are reported in Table 2 and Figure 5 respectively) has been considered since, among the hulls considered in [1], it is the most similar to the “Podded” craft (even if evidently differences exist).

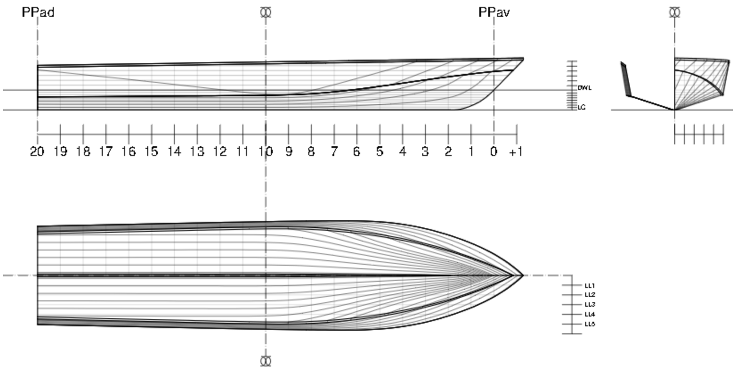


Figure 5 - TB45 hull: Construction plan

CHARACTERISTIC	VALUE
Length [m]	1
Beam [m]	0.22
Draft [m]	0.041
Wetted Surface [m^2]	0.041
Deadrise [°]	18°
Displacement [kg]	3.7

Table 2: main data [1]

In [1] an experimental campaign in a rectilinear towing tank equipped with a PMM with 6 components balance were performed. Among the various tests, static drift tests have been considered in the present work, while yaw-related tests, as already remarked, will be considered in future activities. In table 3 the tested conditions for the TB45 hull are reported, together with the cases simulated numerically (marked).

		F_N						
		0.355	0.484	0.645	0.904	1.194	1.484	1.807
β [°]	0	✓	-	-	✓	✓	-	✓
	10	✓	-	-	✓	✓	-	✓
	20	-	-	-	-	-	-	-

Table 3 – Available model tests and simulations (marked)

In general, the model was free to heave, pitch and roll at the given drift angle and Froude number. The same conditions have been then simulated numerically, adopting the commercial RANS code Star-CCM+. This is a viscous flow solver based on a finite volume approach. It implements many features useful to solve most of the real flow problems related to the naval field. In particular, in the present simulations the DFBI (Dynamic Fluid Body Interaction) model with an overlapping mesh has been used. This approach allows to freely move the body-fitted mesh around the hull following the 3-dimensional rigid body equations without using mesh morphing techniques (as shown in Figure 6). The free surface has been solved by means of a Volume of Fluid approach (VoF [6]) where the amount of fluid inside each cells is computed solving the related convective partial differential equation by means of an high-order scheme (HRIC [7]). Following previously adopted and validated setup for these type of simulations (more detail can be found in [8] and [9]), proper mesh refinements have been used for a total cells amount of about 2 millions. In Figure 6 a sketch of the adopted mesh with relative refinements is reported.

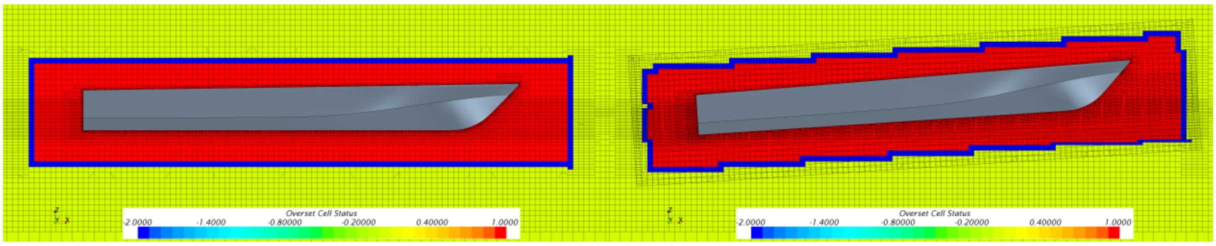


Figure 6 – DFBI approach and used mesh

In the figure 7 the results for the longitudinal force in both cases (0° and 10° drift angle) and the lateral force, yaw moment and heel angle at 10° drift angle are represented as a function of the Froude number and compared with experimental results.

The comparison of the numerical predictions of the hull drag are in reasonable agreement with the experimental data for all the velocities in correspondence to the purely longitudinal motion. However, the drag force variation in function of the drift angle presents a different trend. In particular, an increase of the resistance is predicted numerically at all speeds (except in correspondence of F_N=1.2), while in the experiments it appeared to reduce (apart at the lowest velocity, for which the trend is equal). Differences are rather limited but still remarkable; it has to be underlined, however, that the reduction of resistance observed during experiments appears anomalous, thus further investigations will be carried out in future to better analyse this feature and the possible reasons of discrepancy.

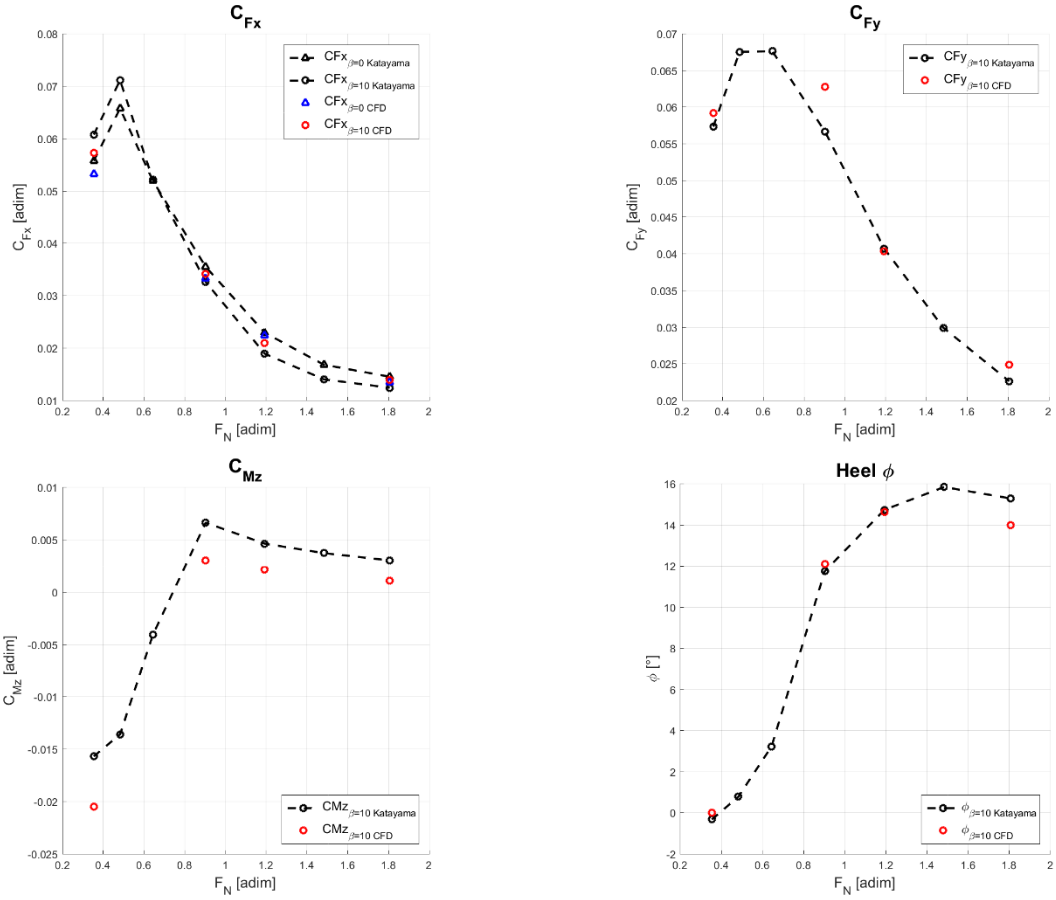


Figure 7- TB 45 – Comparison between numerical and experimental results

Considering the lateral force and the yaw moment, the global tendency is very well captured in both cases, allowing also to obtain the change of sign of C_{MZ} at increasing Froude number, typical of planning boats behaviour. The absolute values are very well captured for the lateral force coefficient, while a certain discrepancy exists for the yaw moment coefficient, implying a shift towards bow (by slightly more than 5% of the total length) of the center of the lateral force. Finally, a very good agreement between predicted and experimental values of the heel angle is evident, allowing to have a rather high confidence on the global accuracy of the method.

Considering the promising results obtained for the TB45 model, similar simulations have been performed for the test case used in [4], as discussed in the following section.

Test Case 2 – "Podded" – CFD + SIMULATION

In the case of the "Podded" boat, similar calculations have been carried out, thus adopting the same calculation setup described previously for the TB45 test case. In this case however the aim was to obtain the forces (and related coefficients) for the 4 DOF simulator previously described. As a consequence, contrarily to the TB45 test case, for which the boat was free to roll, calculations were carried out at prescribed roll angles. Moreover, since interest was posed on the simulation of tight manoeuvres with high pod angles and consequently high drift angles, calculations were carried out with higher values of the drift angle itself. This results in a higher number of cases for each boat speed, even limiting the number of considered angles (0°, 10° and 20° for both heel and drift). As a consequence, in order to limit the computational efforts (considering the available computational resources and time), only two speeds were considered, i.e. the boat approach speed to the manoeuvre and the minimum speed recorded during manoeuvres; the various conditions for which calculations have been carried out are summarized in Table 4. This may be considered a minimum set of calculations to characterize the boat maneouvring behaviour; in the intermediate velocities, trends have been interpolated considering experimental tendencies of the TB45 model. In future, it is planned to enlarge the range of analysis also to other conditions to better characterize the transients of the manoeuvre.

U= 24 kts		**ϕ [°]**		
		0	10	20
β [°]	0	✓	✓	✓
	10	✓	✓	✓
	20	✓	✓	✓

U= 32 kts		**ϕ [°]**		
		0	10	20
β [°]	0	✓	-	-
	10	✓	✓	✓
	20	✓	✓	✓

Table 4- "Podded" Test case – Numerical simulations conditions

The complete results of the various calculations carried out are omitted for the sake of shortness (they will be reported in a future paper). In general, however, some trends have been found in terms of difference between calculations and results directly provided by Henry regressions; these trends are summarized as follows:

- Longitudinal force coefficient C_{FX} presents increasing values with drift angles, while in the case of Henry regressions resistance has low variations (and an opposite trend, as already found for TB45 case); discrepancies tend to increase with drift angle.
- Lateral force coefficient C_{FY}, even if showing a general agreement (in terms of influence of heel and drift) is higher in numerical calculations than in Henry regressions; this results in a lower drift angle during the turn and, as a consequence, in a tighter manoeuvre due to the reduction of the yawing moment (it has to be kept in

mind that the yaw moment due to drift is opposite to the case of the displacement boats).

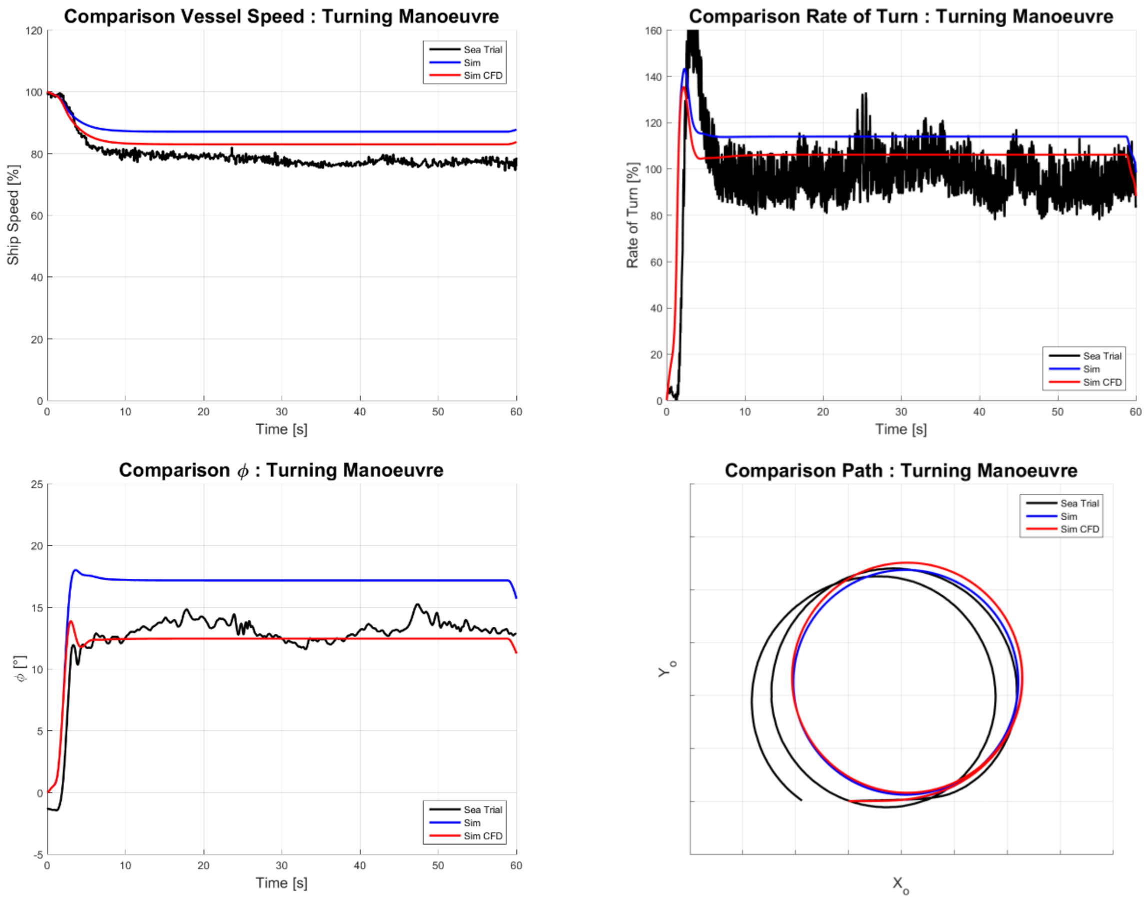
- For the yaw moment coefficient C_{MZ} a tendency to shift the force aft is present; this results in a more stable behaviour of the boat.
- Finally, heeling moment C_{MX} presents a trend similar to the regressions one, allowing to obtain a rather similar equilibrium roll angle at different drift angles, even if discrepancies are present, especially for the higher drift angles.

Simulations

In the present paragraph, the results of manoeuvring simulations carried out substituting the numerically obtained coefficients are reported and compared with sea trials measurements and previously obtained simulations with the coefficients based on Henry regressions. The simulations were carried out imposing constant RPM of the propellers (thus, excluding the part related to engine and automation), consistently with the sea trials results.

Two manoeuvres are considered, i.e. a tight turn at maximum allowed pod angle at maximum speed and a sort of ZigZag manoeuvre with 20° pod angle; in the second case, it has to be remaked that, due to the fast dynamics of the manoeuvre, the pod orders were not given at the prescribed time.

In both cases, boat speed, rate of turn and roll angle are reported. Moreover, heading angle and trajectory are reported for the ZigZag manoeuvre and turning circle respectively. Results are non-dimensionalised (or omitted, as in the case of the turning circle trajectory) for industrial reasons.


Comparison Vessel Speed : Turning Manoeuvre

Comparison Rate of Turn : Turning Manoeuvre

Comparison ϕ : Turning Manoeuvre

Comparison Path : Turning Manoeuvre

Figure 8- "Podded" test case – Turning circle manoeuvre at max speed and pod angle (in blue the original model, in red the model corrected using CFD results)

Considering the turning circle manoeuvre (Figure 8), it is clear that the modified coefficients do not result in significant modifications of the trajectory; this is mainly due to the opposite effect of the variation of C_{MZ} and C_{FY} coefficients, with a destabilizing and stabilizing tendency, which compensate each other. From this point of view, however, it has to be remarked that the effects of the single coefficients are rather large (up to 15-20% when considering the tactical diameter), underlining the importance of a direct approach.

Considering the velocities, it may be seen that the new simulations are in better agreement both in terms of ship speed and rate of turn (apart the initial peak value), with a higher speed reduction during turn, due to the increased resistance at higher drift angles; this results also in a much better capturing of the heel angle.

Considering the ZigZag manoeuvre (Figure 9), differences are again rather limited, especially considering heading angle and rate of turn. A tendency similar to the one observed for turning circle manoeuvre is evident for both ship speed (with a higher reduction, consistent with sea trials) and heel angle (with a reduction of the peaks, particularly evident for the first overshoot).

It has to be remarked that the manoeuvre was reproduced by imposing the same pod angle time history recorded during sea trials. As a consequence, due to the fast dynamics of the boat, slight shifts result in higher discrepancies in the heading angle. The good agreement between simulations and experimental data is anyway testified by the rate of turn time history (with except of the larger peaks on one side of the turn). It is important to underline again that, even if the new simulations with the CFD results provide small differences with respect to the original ones, the variation of a single hydrodynamic coefficient resulted in a much higher effect.

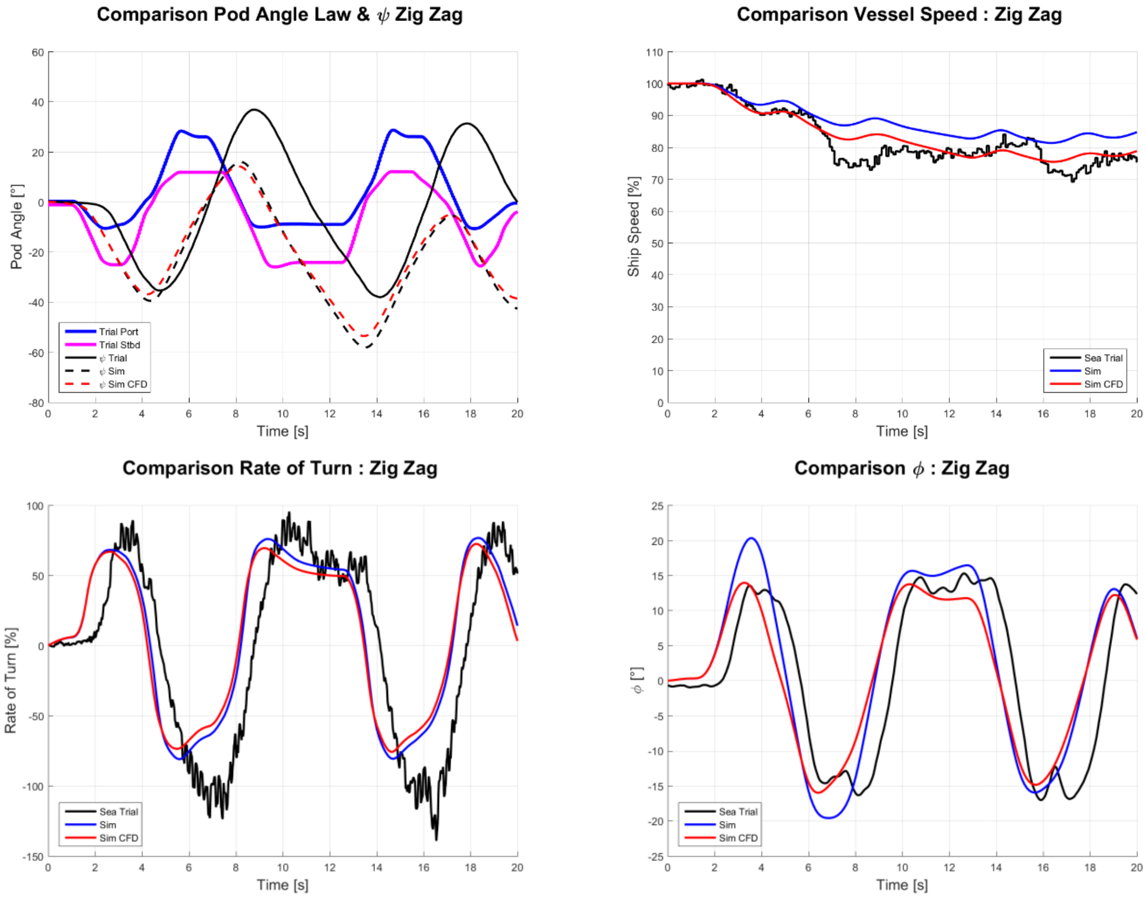


Figure 9- "Podded" test case – ZigZag manoeuvre at max speed (in blue the original model, in red the model corrected using CFD results)

CONCLUSIONS

In the present paper, an approach for the direct evaluation of the manoeuvrability coefficients of planing boats has been presented. The proposed approach has been applied at first to reproduce a set of PMM tests whose results are available in literature; then, the same approach has been used to evaluate the coefficients of the previously developed 4+2 DOF manoeuvrability model. The resultant simulation results show a better agreement with sea trials than previous ones, thus underlining the feasibility of the present approach.

It has to be remarked that presently, due to time restrictions, only pure drift tests have been considered, while the forces related to yaw rate (and also to combined effects) are still evaluated by means of semi-empirical formulations. It is planned in future to investigate also the feasibility of evaluating these forces in order to have a complete approach.

Moreover, in future it is planned also to perform calculations for a larger set of combinations of boat speed, heel and drift angles.

REFERENCES

1. Katayama T., Kimoto R., Ikeda Y. (2005) Effects on running attitudes on manoeuvring hydrodynamics forces for planning hulls, *Int.Conf. on Fast Sea Transp., FAST'2005,* June 2005, St. Petersburg, Russia.
2. Henry C.J. (1975) Calm Water Equilibrium, Directional Stability and Steady Turning Conditions for Recreational Planning Craft, *Report SIT-DL-75-1851,* Stevens Institute of Technology, Davidson Laboratory.
3. Altosole, M., Figari, M., Viviani, M. (2009) 6 Dof Simulation of Maneuvering and Propulsive Performance of a Waterjet Propelled Mega Yacht, *10th Int. Conf. on Fast Sea Transp. (FAST 2009),* October 5-8, Athens, ISBN: 978-960-254-686-4.
4. Ircani, A., Martelli, M., Viviani, M., Altosole, M,. Podenzana Bonvino, C., Grassi, D., Propulsion and steering effects on dynamics of high speed craft, *Proc. 10th Symposium on High Speed Marine Vehicles (HSMV 2014)* – Naples, 15-17 October 2014, p.1-12
5. Ircani A., Martelli M., Viviani M., Altosole M., Podenzana-Bonvino C., Grassi D., A Simulation Approach for Planing Boats Propulsion and Manoeuvrability *Trans RINA, Vol 158, Part B1, Intl J Small Craft Tech, Jan-Jun 2016*
6. Ferziger J.H., Peric M. ˇ , 2002, Computational Methods for Fluid Dynamics, Springer, Berlin
7. Muzaferija S., Peric M., Sames P., Schelin T., 1998, A two-fluid NavierStokes solver to simulate water entry, Proc. Twenty-Second Symposium on Naval Hydrodynamics
8. Diego Villa, Giovanna Vatteroni, Stefano Brizzolara (2009) CFD Calculation of Planing Hulls Hydrodynamic Characteristics Proceeding of Star European conference 2009, London United Kingdom, 23-25 March 2009
9. M Ferrando, S Gaggero and D Villa (2015) Open Source Computational of Planing Hull Resistance Trans. RINA, Vol 157, Part B2, Int. J. Small Craft Tech., Jul-Dec 2015, DOI No: 10.3940/rina.ijsct.2015.b2.172