



HAL
open science

Tackling Modern Sailing Challenges with a CFD-based Dynamic VPP

Pierre Robin, Alban Leroyer, David de Prémorél, Jeroen Wackers

► **To cite this version:**

Pierre Robin, Alban Leroyer, David de Prémorél, Jeroen Wackers. Tackling Modern Sailing Challenges with a CFD-based Dynamic VPP. Innov'Sail 2023, May 2023, Lorient, France. hal-04102794v1

HAL Id: hal-04102794

<https://hal.science/hal-04102794v1>

Submitted on 22 May 2023 (v1), last revised 23 May 2023 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Tackling Modern Sailing Challenges with a CFD-based Dynamic VPP

Pierre Robin

LHEEA Lab - Centrale Nantes/CNRS - Finot-Conq, France, pierre.robin@ec-nantes.fr.

Alban Leroyer

LHEEA Lab - Centrale Nantes/CNRS, France.

David de Prémoriel

Finot-Conq Architectes Navals, France.

Jeroen Wackers

LHEEA Lab - Centrale Nantes/CNRS, France.

Abstract. A dynamic Velocity Prediction Program (VPP) integrated in a Computational Fluid Dynamics (CFD) code is described. The program computes aerodynamic forces and directly inputs them to the CFD solver, which solves both the flow and the motions of the boat. The VPP code controls the heel of the boat and optimises a sail power parameter for a given True Wind Angle and True Wind Speed. This approach allows naval architects to swiftly and precisely compare several yacht designs in real sailing configurations using only a few CFD computations. Several advanced features of this program are covered in this paper including convergence criteria, automatic grid refinement, foil fluid-structure interaction, multiple aerodynamics models and rudder control.

Keywords: CFD; VPP; sailing; hydrofoil; optimisation; FSI.

NOMENCLATURE

C_x, C_y	Aerodynamic Surge and Sway coefficient [-]
F_x, F_y	Aerodynamic Force along x-axis and y-axis [N]
e	Leeway angle error [°]
K_d, K_i, K_p	Derivative, Integral and Proportional Gains [-]
Re	Reynolds Number
S	Sail surface [m^2]
α	Average of the Absolute Value of the Deviation from the Mean Value [-]
β	Maximal Absolute Value of the Deviations from the Mean Value [-]
δ	Leeway angle [°]
φ	Radial-Basis Function [-]
ρ	Fluid Density [kg/m^3]
AGR	Adaptive Grid Refinement
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
DoF	Degree of Freedom
FSI	Fluid-Structure Interaction
IMOCA	International Monohull Open Class Association
MS-FCH	Multi-Surface and Flux-Component Hessian
TWA	True Wind Angle
TWS	True Wind Speed
VPP	Velocity Prediction Program

1 INTRODUCTION

Velocity Prediction Programs (VPP) have been used in the design of modern sailing ships for a few decades. For naval architects, these tools allow to assess and compare the performance of several yacht designs and eventually identify the best one, and as computer technology improves so do VPP codes. Classic static VPPs compute the equilibrium of the forces applied to the yacht and most rely on an interpolation performed in a matrix of the hydrodynamic forces.

This matrix, previously obtained with towing tank trials, is now computed using CFD simulations in 80 to 200 configurations (with different combinations of pitch, trim, draft, heel, speed, etc.). Even with the relentless progresses made in this field, such calculations are very expensive in CPU-time. Moreover, with such a process, any change in the hull design means that a new matrix should be computed, since the hydrodynamic forces applied on the yacht are likely to be different. Thus, traditional VPPs are somewhat impractical for hull-shape optimisation. Additionally, the CFD is performed on an isolated hull, so the interactions with the appendages are approximate at best, if not neglected entirely. Furthermore, although ship performance in waves will be a major challenge in coming years for off-shore sailing, predicting motion in a sea state with a VPP remains difficult: it can only be approximated using successive steady-state force inputs.

For these reasons, we developed a dynamic VPP in which the aerodynamic forces are directly applied to the boat during the CFD computation, while the flow solver handles the hydrodynamic forces. This approach results in dynamic changes in all degrees of freedom (DoF), such as trim, sinkage, heel, etc, leading to a coupling between aerodynamic and hydrodynamic effects. Roux et al. (2008) already performed 5-DoF simulations using a coupling between a CFD code solving hydrodynamics and a potential-flow code computing aerodynamic forces for an AC90 yacht. Later, Böhm (2014), Lindstrand Levin and Larsson (2017) and Persson et al. (2021) presented VPPs using CFD solvers to compute hydrodynamic forces and body motions, while aerodynamics rely on an analytical model. The main innovation of our work is the use of modern techniques that have proven to be really useful when simulating a sailing yacht, such as overset grids or free-surface capture.

Indeed, since our VPP program is embedded in the commercial CFD program FINE/Marine, several key advanced features already in the software can be used, such as quasi-static body motions, adaptive grid refinement or modal approach for fluid-structure interactions. In addition to this, other features more tailored to our use have been developed, including a PID-controlled rudder, a sock-mesh approach for foils and VPP-tailored convergence control. By nature, the main objective of this high-fidelity tool is not to provide a complete polar for the studied design, but to compare different designs in key wind conditions all along the design process. It can also be used dynamically, to simulate a yacht in waves for instance, but this is still under development. While this paper will present some of the features developed for ship in waves simulations, it will mainly focus on the search of steady states to optimise the yacht's speed.

The development of this new tool reflects Finot-Conq's strategy to incorporate more high-fidelity simulations in their design process, while limiting the associated CPU costs. The VPP covered in this paper has been used for Finot-Conq's two new IMOCAs (Paprec-Arkéa and For People), launched in early 2023 with the goal of winning the Vendée Globe in 2024-2025.

Section 2 provides details of the VPP algorithm, while section 3 covers the aerodynamic modules. The hydrodynamic solver is discussed in section 4. Finally, section 5 presents results obtained using the VPP.

2 VPP ALGORITHM

Our dynamic CFD-based VPP (Cadence Design Systems and Finot-Conq, 2021), is integrated in the commercial CFD software FINE/Marine. It allows naval architects to optimise boat speed as a

function of the sails trim (represented by a sail power parameter, see Section 3) in a single 5 or 6 DoF computation.

The general process of the VPP is described in Fig.1. The VPP is a module added to FINE/Marine, thus its use requires first to set up a classical FINE/Marine computation. Placing the yacht in a configuration close to its final position (in terms of cardan angles and displacement) will help the simulation to converge and reduce CPU-time. Additionally, the VPP module requires the user to provide a True Wind Angle (TWA), a True Wind Speed (TWS) and some of the yacht's main characteristics (length over all, freeboard height, air draft, etc.).

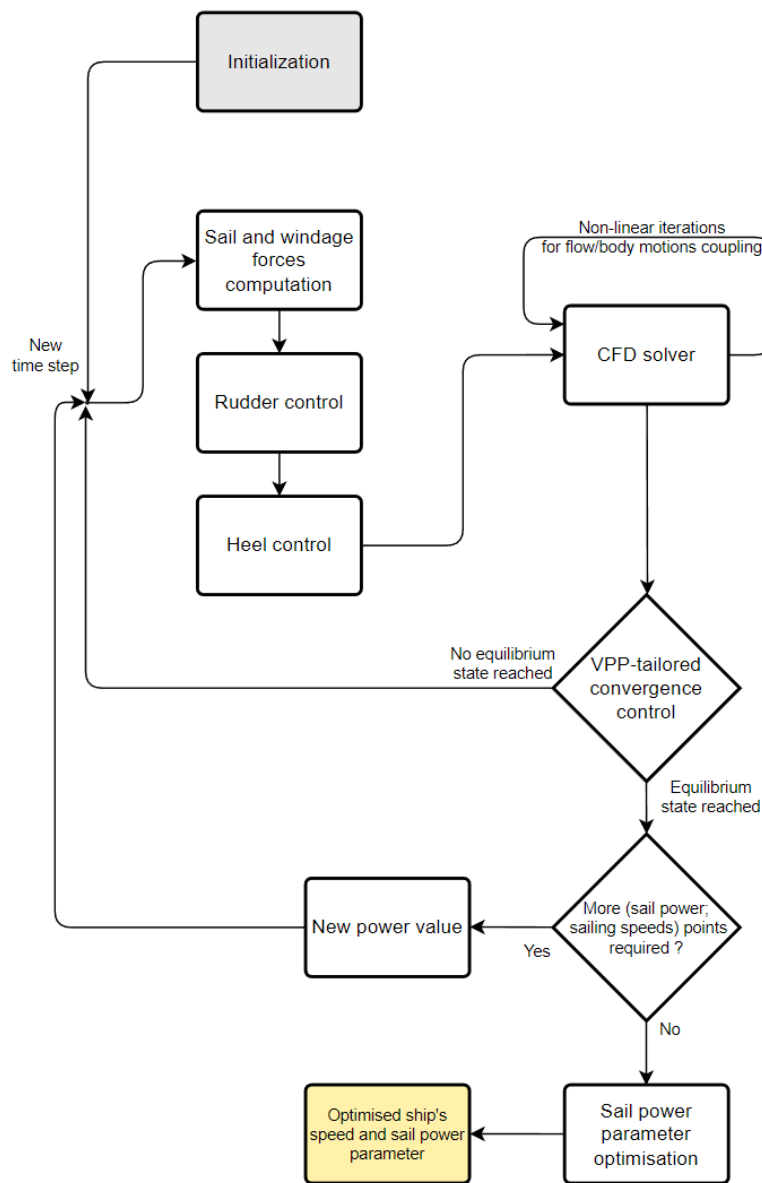


Figure 1. VPP code general process

Once this data is read and FINE/Marine has started, the VPP code updates sail forces at each time step (covered in Section 3), adjusts the rudder angle (Section 2.1), and keeps the heel of the yacht within user-specified bounds (Section 2.3). The resulting forces and moments are then input to the flow solver ISIS-CFD, which solves the flow and the motions of the yacht. During the simulation, the VPP checks if an equilibrium state is reached using a specific set of convergence criteria (Section 2.2). If these criteria are satisfied, a new value for the sail power parameter is chosen by the optimisation algorithm and used in a new stage of the same computation. At the end of the computation, several

equilibrium states have been found (and thus several (speed,sail power) doublets), and the VPP outputs an optimised yacht's speed and sail power parameter for the yacht's geometry and the doublet (TWA,TWS) provided.

2.1 Rudder Models

For course control, two rudder models have been developed. The first consists in an analytical rudder balancing the Mz moment induced by the rest of the forces applied on the boat. When using this method, the user is required to provide a boat geometry without rudder, as well as rudder polars. The rudder's angle is computed from these polars to provide the desired Mz , then all the rudder forces are evaluated at that angle and output to the flow solver.

However, to improve the accuracy of the boat's behavior, and in the scope of carrying out future ship-in-waves simulations, a second approach using a CFD-modelled rudder with a PID controller has been developed. For this approach, the rudder's geometry needs to be included and is placed in an overset domain (see section 4.1). The rudder angle $\delta(t)$ is controlled using, as error e , the difference between the yacht's course angle and a given target bearing. The rudder angle is updated with a given period T using the following law:

$$\delta(t) = K_p * e(t) + K_i * \int_{t-T}^t e(t) dt + K_d * \frac{de(t)}{dt} \quad (1)$$

In addition to the PID-controller, a simplified model of an autopilot's actuator has been implemented with realistic angular speed limitations. This method is still a work in progress, as only linear integration and derivation schemes are implemented and the gains K_p, K_i, K_d are, for the moment, determined by trial-and-error only and will require a lot of fine-tuning using dedicated methodologies.

2.2 Convergence Criteria

To test if the yacht has reached an equilibrium state, specific convergence criteria have been implemented. Indeed, yachts equipped with foils can induce small-scale unsteadiness in the computation, thus requiring to make sure that key physical quantities undergo limited changes around a converged value. To do so, the user has to specify:

- Which physical values (forces, moments, motions quantities) will be studied for convergence,
- After how much simulation time the convergence check is first carried out (t_{start}),
- The amount of time between two convergence tests (t_{laps}),
- The duration (in seconds) of data collected to form a convergence sample t_{cs} ,
- For every physical value: two thresholds to compare the data collected to: α_{ref} and β_{ref} ,

Indeed, for every physical value studied, two additional indicators will be computed: the average of the absolute value of the deviation from the mean value α , whose expression for a quantity x is:

$$\alpha = \frac{1}{t_{cs}} \sum_{t_{cs}} |x - \bar{x}| \quad (2)$$

where \bar{x} is the mean value of the quantity x . But also the maximal absolute value of the deviations from the mean value β , whose expression for a quantity x is:

$$\beta = \max_{t_{cs}} |x - \bar{x}| \quad (3)$$

If for every physical value studied, α and β are inferior to their respective thresholds α_{ref} and β_{ref} , an equilibrium state is considered to be reached. The general workflow of the method is described Fig2:

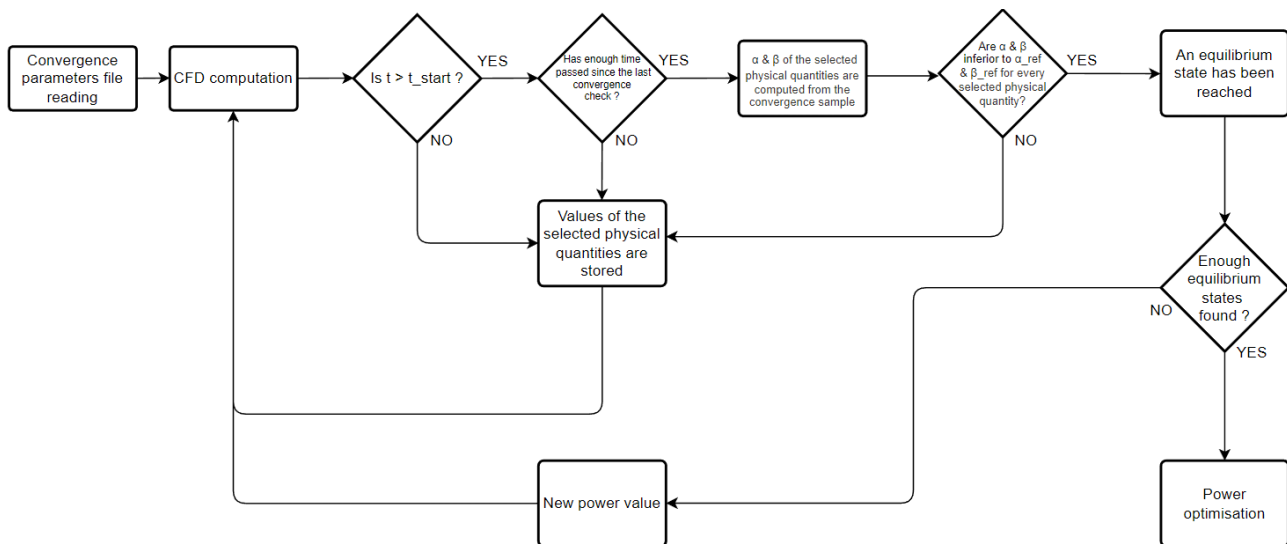


Figure 2. VPP convergence method diagram

2.3 Sail Power Parameter Optimisation

To find the optimum yacht's speed at a given operating point, the sail power parameter, that represents the crew trimming the sails, is optimised. The way this parameter affects the sail forces will be covered in Section 3.

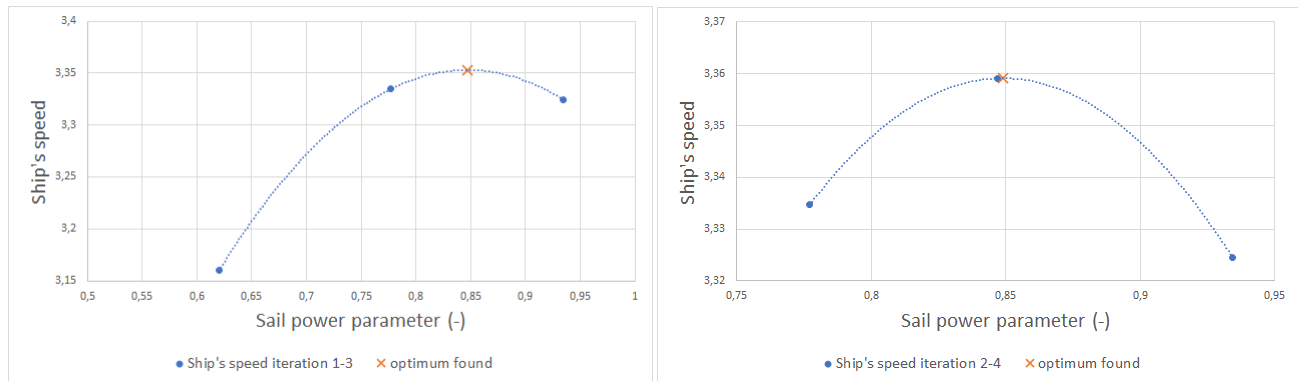
In a single VPP computation, several equilibrium states are reached, each one being associated with an intermediate calculation using a different value of the sail power parameter. A minimum of 3 intermediates calculations is required to calculate an optimum for the sail power parameter. More can be performed if desired, to refine the optimum values obtained. During each intermediate calculation, the sail power parameter may be adjusted if needed to keep the yacht's heel angle between the boundaries specified by user.

The first intermediate computation is initiated with the parameter's maximum value. Once it is considered converged, the sail power parameter is set to its minimum value. Once the second intermediate computation has converged, a third one starts with the mean value of the two previously used. Then the VPP code finds an optimal value for the sail power parameter using parabolic optimisation, based on the first three iterations. If more points are required by the user, the sail power parameter value is set at the computed optimum and another computation starts. At the end of it, a new parabolic optimisation is performed and a new optimum for the sail power parameter is found.

Previous work at Finot-Conq attempted to perform sail power parameter optimisation using other methods, but parabolic optimisation was chosen as the most CPU-efficient. It has also proven to be sufficient as the relationship between speed and sail power parameter is correctly captured by a parabola. For the same reason, multi-criterion optimisation using reefing along with sail power was discarded. Indeed, it is more efficient and more realistic to perform separate VPP runs for different sail plans, due to the discontinuous nature of reefing on a real yacht. An example of results for a 40-foot fast cruiser is presented in Tab. 1 and Fig. 3. The maximal speed of the yacht is not reached for the maximum value of sail power parameter, as a reduced heeling allows the boat to sail faster. The 4th optimisation iteration eventually presented a limited interest here, since the difference in speed obtained at the end of the 4th iteration (0.8488) is really close to the optimum computed at the end of the 3rd iteration (0.8471).

Table 1. Example of results of optimisation for a 40-foot fast cruiser (sail power range: 0.62 - 1).

Iteration	Sail power parameter	Yacht's speed (m/s)	Heel angle °
1	0.9343	3.32	-23.00
2	0.6200	3.16	-11.86
3	0.7772	3.33	-17.39
4	0.8471	3.36	-20.01
Optimum found	0.8488	3.36	not computed



(a) Sail power parameter optimisation using points 1-3 (b) Sail power parameter optimisation using points 2-4

Figure 3. Example of sail power parameter optimisation

3 AERODYNAMIC LIBRARY

An important part of the VPP code lies in the computation of aerodynamic forces. Our VPP can either use analytical models to determine sail aerodynamics or interpolate from a data matrix. The forces and moments applied by the sails to the boat are considered to be a function of AWA , AWS and of the sails' trim, characterized by the sail power parameter. The aerodynamic forces are computed at each time step to account for any change in these quantities.

3.1 Analytical Model

Aerodynamic forces and moments can be computed using analytical methods inspired by the Offshore Racing Congress (ORC) VPP methodology (ORC, 2021). To do so, formulas based on several yacht's sails dimensions are provided to compute sail areas, lift and drag coefficients and center of effort height for each sail. Compared to the ORC formulations, the main sail and the jib are divided in smaller areas in order to take into account the wind gradient. When using this method, the sail power parameter is a coefficient applied linearly to the aerodynamic lift force: if the sail power coefficient is equal to 0.95, this means the crew trimmed the sails to get 95% of the maximum lift.

3.2 Interpolation from Aerodynamics Matrices

In addition to this analytical model, the VPP can also use aerodynamics matrices obtained by external CFD computations, typically those made by the sailmakers. Currently, an interpolation module using cubic interpolations supplies the VPP code with the aerodynamic coefficients for lift and drag. Results for the surge coefficient obtained using this interpolation method for a mainsail and jib aerodynamics matrix are presented in Fig.4.

When using aerodynamic matrices provided by sails designer, the sail power parameter is also the parameter that captures the trim of the sails (sheet and traveller settings) and is one of the variable of

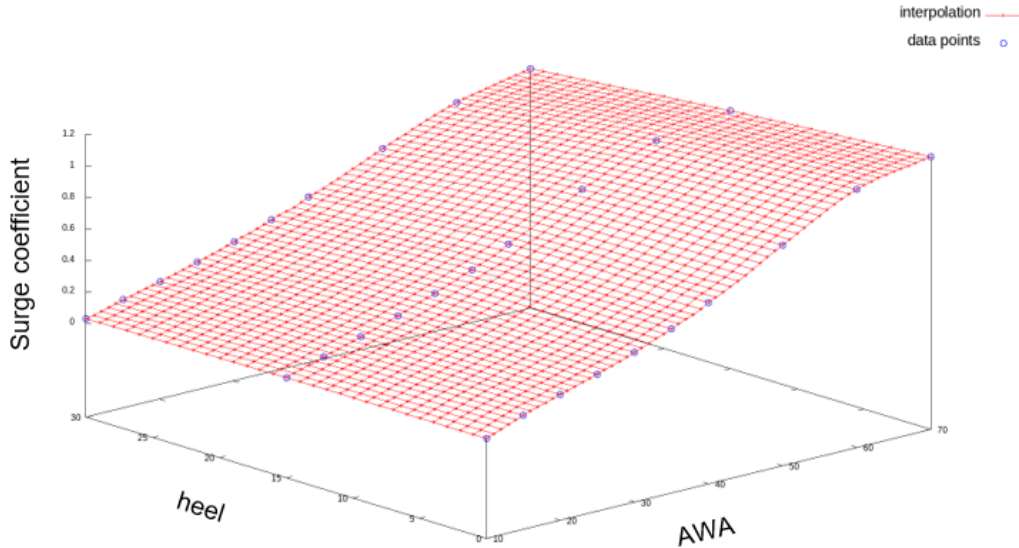


Figure 4. Surge coefficient interpolation using cubic interpolations on AWA and heel. The power is fixed and equal to 1

the interpolation alongside the apparent wind angle and the heel of the boat. The aerodynamic forces are then computed using the following formula :

$$F_x = \frac{1}{2} \rho S C_x V^2 \quad (4)$$

$$F_y = \frac{1}{2} \rho S C_y V^2 \quad (5)$$

with F_x being the aerodynamic force along x-axis, F_y the one along the y-axis, ρ the air' density, S the surface of the considered sail, C_x the surge coefficient, C_y the sway coefficient (both coefficients' values being interpolated from the sailmakers' matrix) and V the velocity of the flow at the sail's effort height (obtained from AWS).

However, it could prove useful to be able to interpolate using more variables, therefore an interpolation method based on radial-basis functions is being developed. For such purposes, several radial-basis functions are available (Volpi et al., 2015), but based on our early results, the radial function $\varphi(r) = r^3$ appears to be an efficient choice to interpolate inside a sail plan's aerodynamic efforts matrix, and it is easy to implement.

3.3 Windage

Windage forces acting on the different parts of the sailing boat (hull, mast, rigging, crew, etc.) are also computed using analytical formulas, inspired by the ORC VPP methodology. The windage forces consider both front and side surface areas of the different elements of the boat. These forces are then added to the sail forces and the sum is input to the hydrodynamic solver as external forces applied on the boat. It is noted that, in some sailmakers' aerodynamic matrices, these forces are already taken into account, thus no additional windage forces need to be computed.

4 HYDRODYNAMIC SOLVER

FINE/Marine is a marine-oriented computing suite, distributed by Cadence Design Systems (formerly Numeca International) and used by many naval architects for various hydrodynamics applications. The suite features an unstructured hexahedral mesher called Hexpress, as well as the flow solver ISIS-CFD. The latter is an incompressible unsteady Navier-Stokes equations solver with various

Reynold-Averaged Navier Stokes (RANS) or RANS/Large Eddy Simulation hybrid turbulence models for multifluid flows which is developed by the METHRIC team of the LHEEA Laboratory. All calculations presented in this paper used RANS equations along $k - \omega$ *SST* turbulence model, with y^+ values defined using FINE/Marine best practices:

$$y^+ = \max \left(y_{min}^+, \min \left(30 + \frac{(Re - 1e^6) * 270}{1e^9}, y_{max}^+ \right) \right) \quad (6)$$

with $y_{max}^+ = 300$, $y_{min}^+ = 50$ and Re the Reynolds Number.

This solver features a mixture-fluid formulation to model the water-air interface (Queutey and Visonneau, 2007; Wackers et al., 2011). The flow equations are discretised in a finite-volume framework, using pressure-velocity coupling obtained through implicit time integration with a Rhie & Chow SIMPLE-type method. The discretisation is face-based. While all unknown state variables are cell-centered, the systems of equations used in the implicit time stepping procedure are constructed face by face. This technique poses no specific requirements on the topology of the cells. Therefore, the grids can be completely unstructured, and cells with an arbitrary number of arbitrarily-shaped faces are accepted.

4.1 Computing Yacht Motions

For our 5 or 6-DoF VPP computations, a coupling between the flow, the external forces and yacht motions is necessary as the motion of the yacht modifies the flow, and as the flow applies forces on the yacht, modifying its kinematics.

Thus, ISIS-CFD uses non-linear iterations inside each single time step to solve both the Navier-Stokes equations and the yacht's dynamics at the same time and perform the coupling between flow and body motion (Leroyer and Visonneau, 2005). For every non-linear iteration the motions of the yacht are updated, the mesh is deformed accordingly and the flow is solved. Forces and moments applied on the yacht can then be computed using the newly obtained flow before a new non-linear iteration starts.

To handle large motions of bodies, ISIS-CFD relies on an overset method, with a finely meshed domain around the body overlapping a background domain and moving through it. These two domains are dynamically coupled using interpolation, either through a least squares approach or with a weighted distance scheme. The VPP optimisation algorithm changes the sail power parameter, thereby inducing major changes in the yacht's attitude, making the use of overset grids a must. When simulating an IMOCA and all its appendages in our VPP, up to 4 overset domains are used: the hull and the keel are within the yacht overset domain (blue in Fig. 5) which also contains two rudder overset domains (in red), as well as the sock-mesh overset domain for the foil (in yellow).

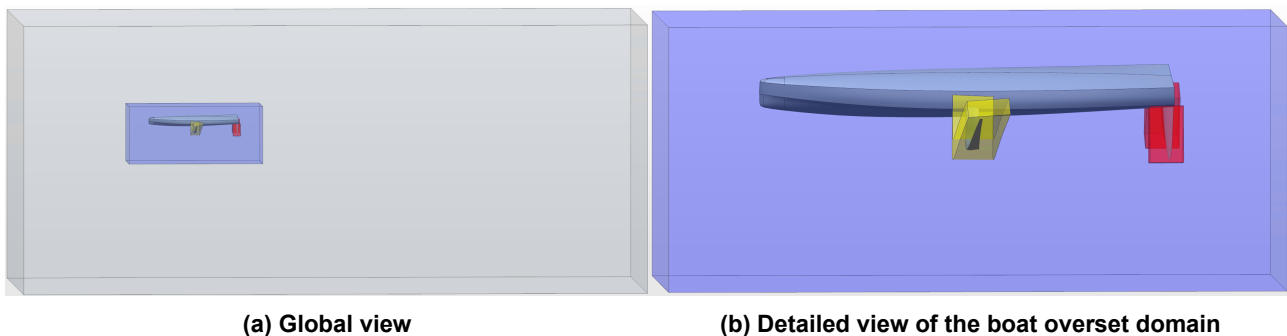


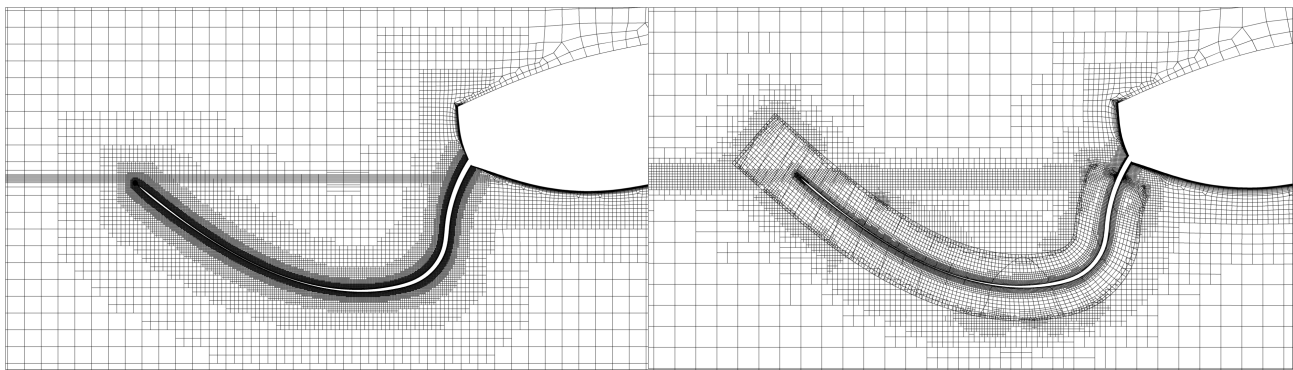
Figure 5. Use of overset domains for a typical IMOCA VPP simulation.

4.2 Adaptive Grid Refinement and Sock-mesh Approach

One of the most important features of FINE/Marine is the adaptive grid refinement (AGR) algorithm, with several available criteria that allow the mesh to be automatically refined locally, during the compu-

tation (Wackers et al., 2017;Wackers, 2021). This powerful tool enhances the capturing of flow details, either for waves, wake flows, or in boundary layers around bodies, especially around hydrofoil edges.

When a good accuracy for the forces applied on bodies as well as a good understanding of the flow in the boundary layer is needed (which is typically the case in calculations involving hydrofoils) the Multi-Surface and Flux-Component Hessian (MS-FCH) criterion is the go-to criterion (Wackers et al., 2022). When using this AGR algorithm, the refinement criterion is based not only on the free-surface position but also on the Hessian of both pressure and velocity. Above all, calculations using the MS-FCH criterion allow users to generate a coarser initial mesh on bodies, and to leave local mesh refinements to the AGR algorithm.



(a) Cut view of the mesh using a box-shaped initial do- (b) Cut view of the mesh using the sock-mesh approach
main

Figure 6. Comparison of meshing methods for IMOCA VPP simulation.

When simulating a boat equipped with foils, box-shaped domains are typically employed in Hexpress (FINE/Marine's mesh generator). For these, the cells are not aligned with the curved foil geometry, so the mesh generator creates many very small cells of mediocre quality to capture the foil (see Fig.6a). To tackle this issue, a good practice consists in using an initial curved overset domain whose shape follows the foil's shape (see Fig.6b) in addition to the yacht's box-shaped domain, as this allows for better-quality initial meshes. Furthermore, the benefits of using the MS-FCH criterion are reinforced when using a sock initial mesh for the foil, since the initial mesh is of better quality and lighter, thus leading to better precision and CPU-time savings (Robin et al., 2022).

4.3 Fluid-structure Interaction

For IMOCA foils of roughly 6 meters length, the deflection at the tip can reach up to 1 meter in certain sailing conditions. These large deformations lead naval architects and engineers to take into account fluid-structure interactions for these appendages. Indeed, calculations and experience both show that fluid-structure interaction plays a major role in an IMOCA's foil's performance. Its bending (mostly rotation of sections around the length-wise axis of the boat) modifies the ratio of vertical and lateral lift. Its torsion has a major influence on the lift distribution, and as a consequence on the lift/drag ratio. The combination of both effects, depending upon the design of the foil, can have a stabilizing or a destabilizing influence on the yacht's behavior at sea. Accurate capture of the foil's deformations is therefore essential to correctly assess the performance of foiling or foils-assisted boats, both in a VPP-optimised steady equilibrium or dynamic, for example in waves.

As of now, FINE/Marine handles fluid-structure interaction through a modal approach (Leroyer, 2021; Mouton et al., 2018). The first eigenmodes deformations of the structure are computed in an external finite element solver and input to the flow solver. During the computation, structural deformations are obtained by computing the temporal evolution of the amplitude of these selected eigenmodes through a modal equation solved internally. This approach allows for CPU-time savings, since this FSI approach does not need to interact directly with a structural solver during the flow resolution. In

addition to this, using a third-part external FEA solver allows to account for any internal design, shape or material characteristics. The behaviour of the structure is computed using an internal module, and so is the rigid motion. The sock-mesh approach simplifies the handling of the deformation of the mesh around the foil as the domain is of limited size and its curves follow the foil's shape.

However, the modal approach does not take into account non-linearities, and further works will compare this method to another approach where a coupling with a beam model structural solver is made. For the naval architect, the beam approach is also interesting as it does not require the separate calculation step of the first deformation eigenmodes, and because the description of a foil as a beam, which is usually known, is directly input to the code.

5 RESULTS

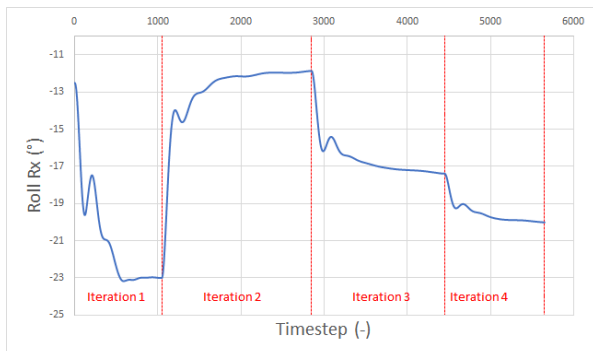
5.1 40-foot Fast Cruiser

A VPP simulation has been carried out for a modern 40-foot fast cruiser, using the analytical aerodynamic model and the analytical rudder model covered previously. The parameters of the simulation are described in Tab. 2:

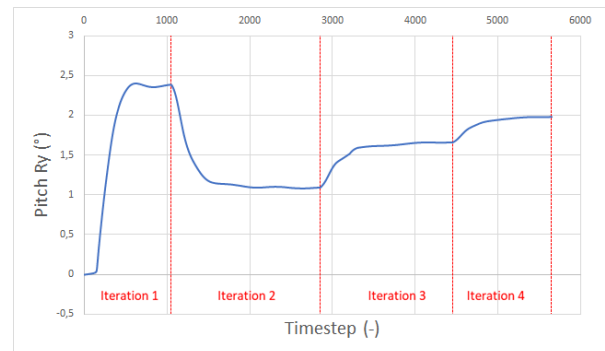
Table 2. Computation parameters for the 40-foot fast cruiser simulation

TWS	TWA	Initial yacht's speed (m/s)	Sail plan	Power range
10kts	50 °	8 kts	Mainsail + Jib	0.62-1

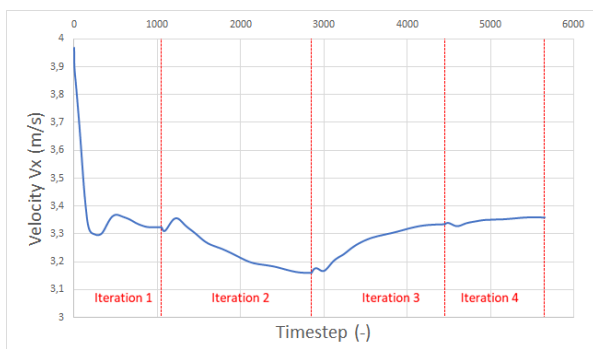
In addition to Tab. 1 and Fig. 3, results for several physical quantities are presented in Fig. 7.



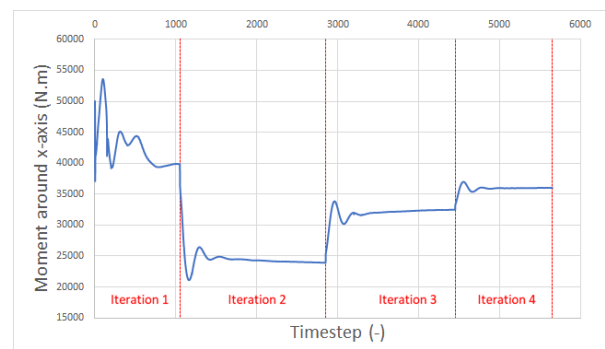
(a) Evolution of yacht's roll angle during the computation



(b) Evolution of yacht's pitch angle during the computation



(c) Evolution of yacht's speed along x-axis during the computation



(d) Evolution of yacht's moment around x-axis during the computation

Figure 7. Results for a 40 feet fast cruiser

The impact of the change in sail parameter power can be clearly observed. When initially set to the maximum value (1.0), the sail power parameter eventually reaches a smaller value (0.9343) due to the maximal heeling being attained. Then the sail power parameter is set to its minimal value (0.62), the boat rights itself, but at the cost of a loss of speed. The parameter is then set to an intermediate value (0.7771), at which the boat sails faster than for the maximal sail power parameter value. Using these results, a first optimised point is computed, with a sail power parameter of 0.8470. When used as the input of a fourth iteration, it brings a better yacht's speed, and the final parabolic optimisation eventually finds an optimal sail power parameter value of 0.8488.

5.2 IMOCA

The following calculations have been made during the design campaign of two IMOCA's for the Vendée Globe 2024. The simulated yacht has its canting keel and the leeward side foil. The interpolation in an aerodynamics matrix is used, as well as the analytical rudder model. Other parameters of the calculation are listed in Tab. 3.

Table 3. Computation parameters for the IMOCA 60' VPP simulation

TWS	TWA	Initial yacht's speed (m/s, normalized)	Sail plan	Power range
20kts	135 °	1	Mainsail + Code Zero	0-1

Results of the optimisation are presented in Tab. 4 and Fig. 8. For confidentiality reasons, some results have been normalized. The effect of the sail power parameter on various physical quantities can be observed in Fig. 9 and the effect on the yacht's attitude in Fig. 10. In this case, the maximum heel angle is set at 20° for external reasons. At the end of the first 3 iterations, it appears that the maximum speed is attained for the maximum power parameter, and no further iteration is necessary. A larger maximum heel angle would likely result in a similar result.

Table 4. Results of optimisation for an IMOCA.

Iteration	Sail power parameter	yacht's speed (m/s)	Heel angle °
1	0.9367	12.88	-19.99
2	0.0000	10.67	-10.14
3	0.4683	11.95	-14.23
Optimum found	0.9367	12.88	-19.99

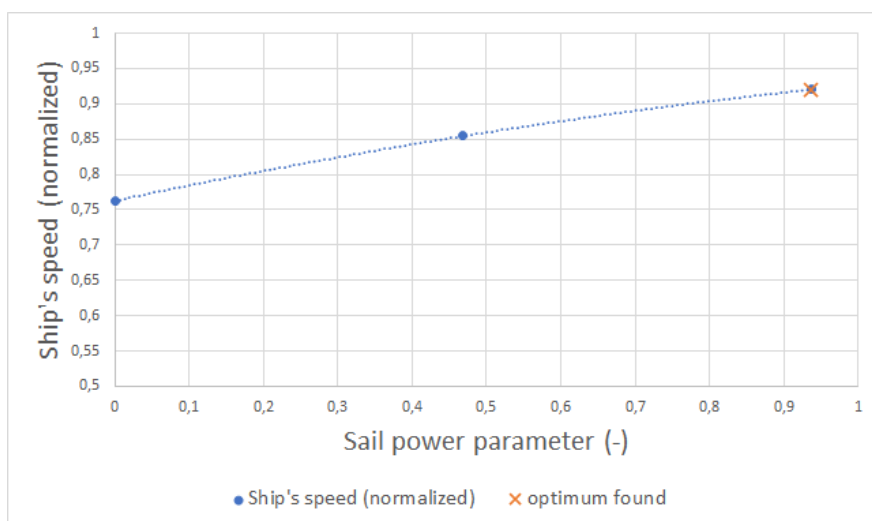
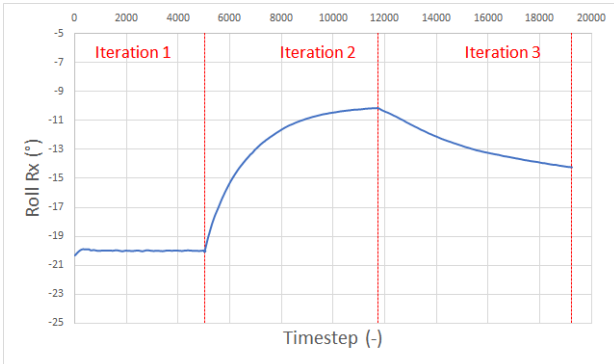
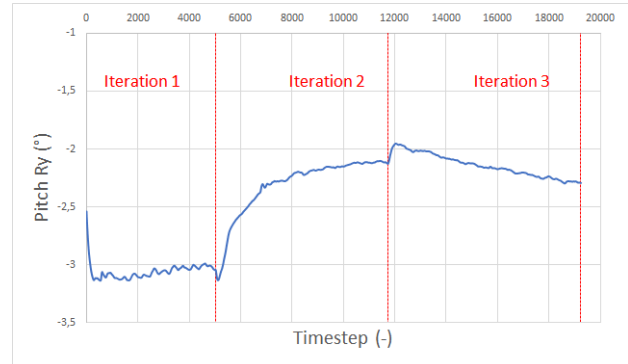


Figure 8. Sail power parameter optimisation for an IMOCA.

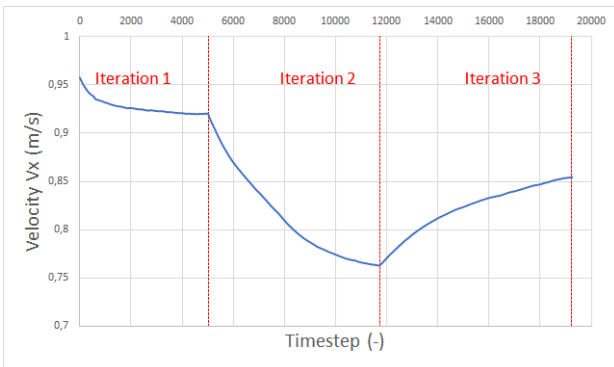
For this particular computation, it was expected to obtain the maximal sailing speed for the maximal value of the sail power parameter. Hence, fine convergence criteria were applied to the first stage of the computation, where the VPP code looks for an equilibrium state associated to a sail power parameter equal to 1. Coarser convergence criteria were applied during the following iterations, which have inferior sail power parameters value, to reduce CPU-time as it was an industrial project.



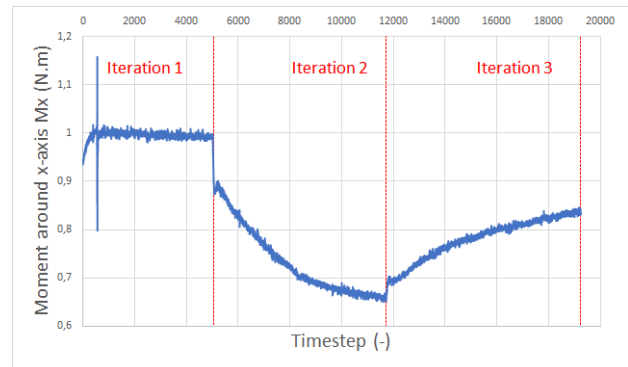
(a) Evolution of yacht's roll angle during the computation



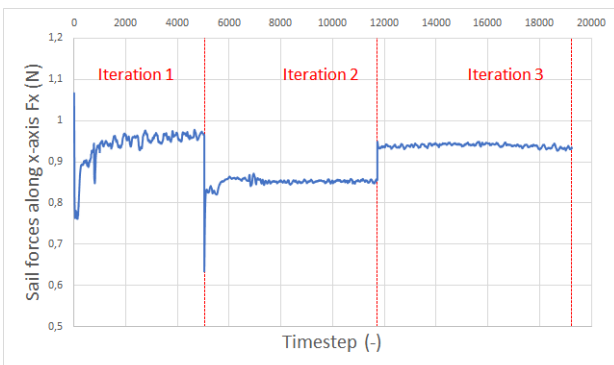
(b) Evolution of yacht's pitch angle during the computation



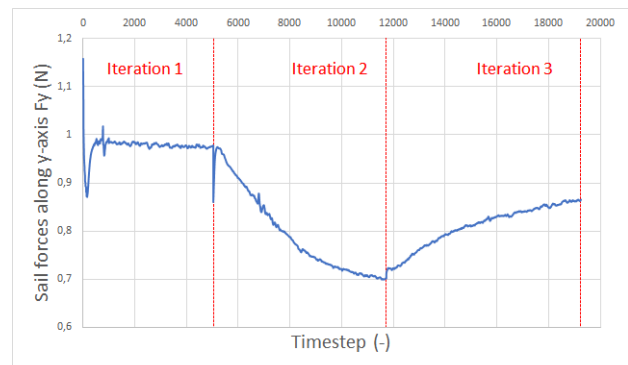
(c) Evolution of yacht's speed along x-axis during the computation



(d) Evolution of yacht's moment around x-axis during the computation



(e) Evolution of force along x-axis provided by the sails during the computation



(f) Evolution of force along y-axis provided by the sails during the computation

Figure 9. Results for an IMOCA 60' VPP simulation

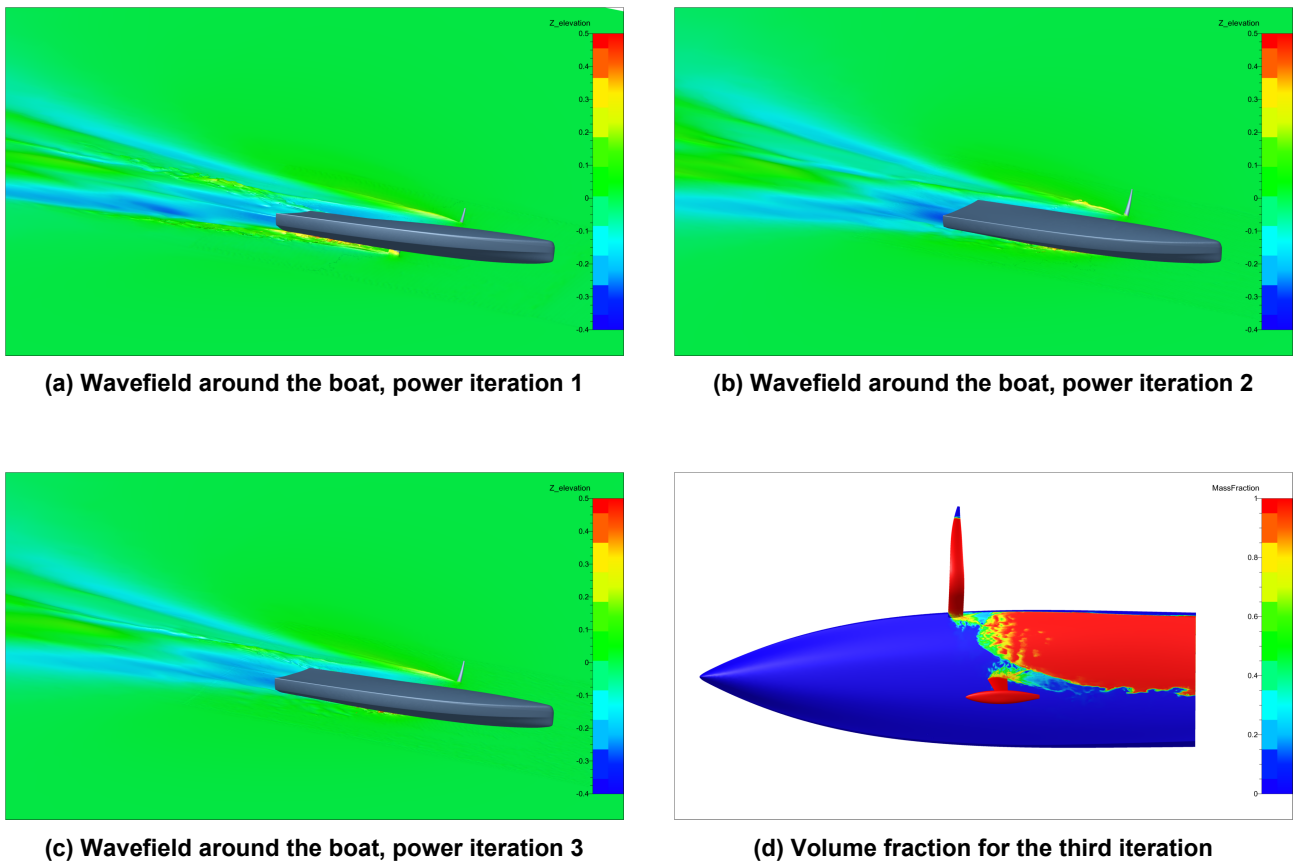


Figure 10. Results for an IMOCA 60' VPP simulation

6 DISCUSSION

When using our VPP, naval architects are able to obtain precise results to assess their designs' performance. For sailing yachts without foils, a single operating point, defined by a single (TWA, TWS) doublet, is typically calculated within half a day on a recent dual-AMD 7773X computer. For the purpose of comparing it to another design, a design can be correctly assessed with 5 to 10 carefully chosen operating points. In comparison, on the same machine, the 100+ computations required to build the hull's hydrodynamics matrix that feeds a traditional static VPP would take over a week, and require much more user time to setup and post-process.

For racing yachts with foils, the computation time is significantly longer, because of the larger number of cells required to capture the geometry of the foil with sufficient accuracy, and because of the occasional larger motions. The computation time of the required operating points is comparable to that of the hull's hydrodynamic matrix.

In this case (and in the previous case as well), the advantage of our VPP lies in the precision of the method: The interactions between the hull and the appendages, and between the different appendages, are entirely taken into account as are the surface-piercing effects of the foils. Calculations have shown these interactions to be very significant, leading to differences in leeway, for example, of up to 2° between our VPP and a static VPP with separate lifting line models for the appendages. This approach is therefore complementary to traditional VPPs which can give more operating points and can be calibrated using the high-fidelity results.

Being able to capture the behavior of the yacht in waves is currently a major topic of development in ocean-going racing yachts. Thanks to the developments currently being implemented, the ability

to carry out high fidelity 6-DoF dynamic simulation of a foiling boat in these more realistic sailing conditions will be an added benefit of this VPP.

7 CONCLUSION

The aim of this work is to develop a VPP that will allow naval architects to perform high-fidelity studies of modern sailing boats using state-of-the-art CFD techniques. This paper showed through two yachts that such results can easily be obtained. Moreover, in the scope of industrial use, this VPP program permits to perform high-fidelity studies for a few operating points of a design, in a way that is complementary to traditional VPPs.

Like many VPPs, the results obtained using this program would need comparison to experimental or real values to correctly obtain validation. However, based on Finot-Conq's experience and on a few sea trials, the results provided by the VPP are very satisfying.

Future work includes beam-elements for FSI and their comparison to the modal approach. Ventilation and cavitation will definitely be addressed, as well as a convergence method better tailored for ship-in-waves simulations.

REFERENCES

- Böhm, C. (2014). "A Velocity Prediction Procedure for Sailing Yachts with a hydrodynamic Model based on integrated fully coupled RANSE-Free-Surface Simulations." PhD thesis. TU Delft.
- Cadence Design Systems and Finot-Conq (2021). "Finot-Conq & Numeca create a CFD-based and dynamic VPP." In: <https://www.numeca.com/finot-conq-and-numeca-create-a-cfd-based-and-dynamic-vpp>.
- Leroyer, A. (2021). "Efficient and robust FSI RANSE simulations around elongated bodies for hydrodynamic applications, minimally intrusive for the beam solver." In: *Proceedings of MARINE 2021*. Online.
- Leroyer, A. and M. Visonneau (2005). "Numerical Methods for RANSE Simulations of a Self-Propelled Fish-like Body". In: *Journal of Fluids and Structures* 20.7, pp. 975–991.
- Lindstrand Levin, R. and L. Larsson (2017). "Sailing yacht performance prediction based on coupled CFD and rigid body dynamics in 6 degrees of freedom". In: *Ocean Engineering* 144, pp. 362–373.
- Mouton, L., A. Leroyer, G. B. Deng, P. Queutey, T. Soler, and B. Ward (2018). "Towards unsteady approach for future flutter calculation". In: *Journal of Sailing Technology* 3, pp. 1–19.
- ORC, Offshore Racing Congress (2021). "ORC VPP Documentation 2021". In: <https://www.orc.org/rules/ORC>.
- Persson, A., L. Larsson, and C. Finnsgård (2021). "An Improved Procedure for Strongly Coupled Prediction of Sailing Yacht Performance". In: *Journal of Sailing Technology* 6.01, pp. 133–150.
- Queutey, P. and M. Visonneau (2007). "An Interface Capturing Method for Free-Surface Hydrodynamic Flows". In: 36.9, pp. 1481–1510.

Robin, P., A. Leroyer, J. Richeux, D. de Prémorél, and J. Wackers (2022). “Starting off the right foot with foil sock approach and AGR criterion.” In: *Proceedings of 24th Numerical Towing Tank Symposium*. Zagreb, Croatia.

Roux, Y., M. Durand, A. Leroyer, Queutey P., M. Visonneau, J. Raymond, J-M. Finot, F. Hauville, and A. Purwanto (2008). “Strongly coupled VPP and CFD RANSE code for sailing yacht performance prediction.” In: *Proceedings of 3rd High Performance Yacht Design Conference*. Auckland, New Zealand.

Volpi, S., M. Diez, N. Gaul, H. Song, U. Iemma, K. Choi, E. Campana, and F. Stern (2015). “Development and validation of a dynamic metamodel based on stochastic radial basis functions and uncertainty quantification”. In: *Structural and Multidisciplinary Optimization* 51, pp. 347–368.

Wackers, J. (2021). “Industrial application of adaptive grid refinement – the case of FINE/Marine.” In: *Proceedings of ADMOS 2021*. Online.

Wackers, J., G. B. Deng, E. Guilmineau, A. Leroyer, P. Queutey, M. Visonneau, A. Palmieri, and Liverani A. (2017). “Can adaptive grid refinement produce grid-independent solutions for incompressible flows?” In: *Journal of Computational Physics* 344, pp. 364–380.

Wackers, J., G. B. Deng, A. Leroyer, C. Raymond, and J. Richeux (2022). “Towards automatic resistance evaluation using mesh adaptation.” In: *Proceedings of 24th Numerical Towing Tank Symposium*. Zagreb, Croatia.

Wackers, J., B. Koren, H. C. Raven, A. van der Ploeg, A.R. Starke, G. B. Deng, P. Queutey, M. Visonneau, T. Hino, and K. Ohashi (2011). “Free-surface viscous flow solution methods for ship hydrodynamics”. In: *Arch Comput Meth Eng* 18, pp. 1–41.