VI International Conference on Computational Methods in Marine Engineering
MARINE 2015
F. Salvatore, R. Broglia and R. Muscari (Eds)

ON THE FLUID DYNAMIC DESIGN AND OPTIMIZATION OF SAILING YACHTS HULL AND APPENDAGES USING A COMPLETE OPEN SOURCE FRAMEWORK

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Key words: Open Source, Sailing, Optimization, OpenFOAM, OpenVSP, Dakota

Abstract. Naval Architecture preserves both the sketching conceptualism and the engineering pragmatism. As a matter of fact, the heuristic approach behind a sailing yacht technology comes from a tangible amount of experience and knowledge. In this respect, Design and Analysis of Computer Experiments (DACE) represents an efficient tool for improving the overall knowledge on parameter dependency, while a Multi Objective Optimization easily reveal the best choice according to specific project constraints. In this work we propose a fully automated and parametric simulation framework, entirely based on Open Source technology. From an engineering and practical point of view, it is important to understand the real applicability of these tools on complex engineering tasks, such as evaluating the aero- and hydro-dynamic performance of sailing yachts. Due to its reliability, scalability and cost effectiveness, the use of a simulation and optimization framework based on Open Source software represents an attractive option for engineers and designers looking for the best return-of-investment. In order to create the parametric geometry we use *SALOME* and *OpenVSP*, while mesh generation and fluid dynamics simulation are based on *OpenFOAM* technology. The DACE optimization loop and the meta-models construction is done using *DAKOTA*. Finally, data analytics is done using *Python* and *JavaScript* languages, allowing an interactive selections of data regions and/or single point in the design space. Results are shown in terms of Matrix Scatter Plot, Pearson's Coefficient Correlation, Coordinates Plot and Pareto Frontier. As examples of possible applications, we present the optimization framework applied to a dagger-board, a bulb keel, a rigid sail and a sailing yacht hull.

1 INTRODUCTION

The innovation brought in last decades by information technology and applied mathematics has affected, and in some cases irremediably changed, a huge variety of design processes. In the naval field quantities as the hull resistance, propeller efficiency, manoeuvrability and seakeeping behaviour are practical examples of what can be assessed through CFD simulations. Moreover computationally prohibitive procedures as parametric modeling and multi-objective optimization, giving the optimum solutions with regards to a set of design constraints, have now become affordable. These steps close the classic naval architecture design spiral (Figure 1) which considers also the general arrangement, the structures, the weights estimate, the stability and the cost estimate. The possibility of carrying out the entire design process in a tailored way and with the highest know-how over cost ratio has boosted the interest of engineers, naval architect and designers towards Free and Open Source technology.
The sailing yacht behaviour presents an high degree of complexity since the sea state and the wind conditions are basically stochastic inputs and its equilibrium deal with the dynamical balance between hydro- and aerodynamic forces. Generally, calculation of the sail forces and torques are commonly derived from the classic C_L, C_D and C_m diagrams, thus separated from the estimation of the hydrodynamic actions of hull and appendages. Moreover, the overall equilibrium is solved with a Velocity Prediction Program (VPP) taking as an input the true wind speed (TWS) and the angle of attack (AoA) with the boat direction. VPPs iterate on a finite number of possible Apparent Wind Angle (β), Heeling Conditions (ϕ), etc., solving the decoupled 6-DOF rigid body equations until the best yacht setting for the given conditions is reached.

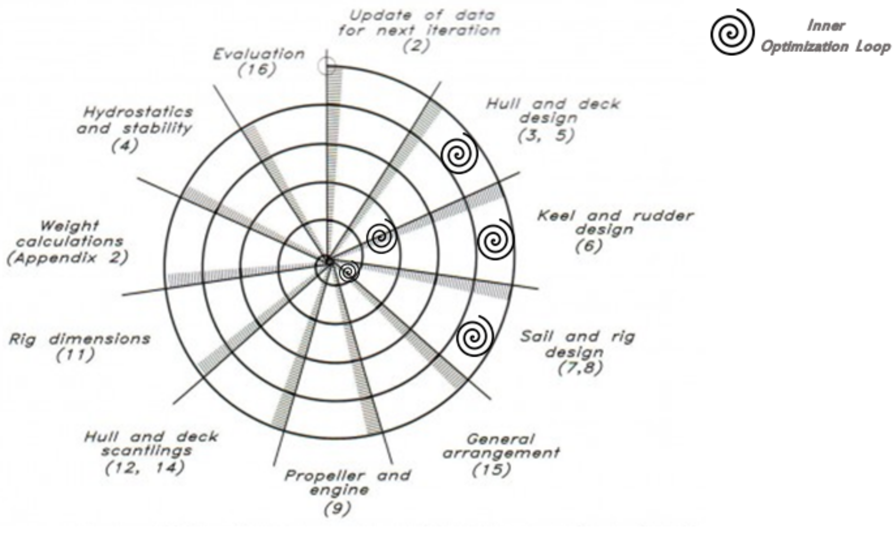


Figure 1: Design Spiral [3]

Since the fluid-dynamic simulation includes several, mutually affecting parameters, Optimization is the engineering process through which the best parameter set is obtained under specific cost functions and design constraints (e.g. lower drag, higher vertical force, same side lift). Moreover, the optimization process leads to a more comprehensive understanding on the single and joined parametric sensitivity. This paper describes a possible optimization framework by using Open Source technology, showing its capability to replace far more expensive field tests.
The first provided example involves the optimization of aero- (rigid sail) and hydro-dynamic appendages (daggerboard, keel and bulb). Due to the particular configuration, faster CFD simulations aimed to the steady solution of a single phase incompressible flow have been used.
The second example describes the enhancement of the hydrodynamical efficiency of a complete hull. In this case CFD simulations have to take into account a more complex unsteady multiphase flow, with an increased simulation cost.

2 WORKFLOW

Figure 2 provides a general scheme of the optimization workflow, together with the used software. The whole process begins with the parametric model of the considered object. When dealing with rather complex geometries (e.g. strong edges, high curvatures) the implementation of a general parametric model is not an easy task. In those cases, it is common practice to simplify the entire shape complexity by lumping different variables. Because of the univocal correspondence between parameter set and shape, the optimum geometry will be defined by the optimum parameter set. This is a key assumption of the whole optimization process. Therefore an "easy-to-script"parametric model is necessary. The following step corresponds to automatic mesh generation. As this can represent the most vulnerable step of the whole process, meshing parameters need to be accurately set in advance in order to fit the alterations of the body shape. Finally, the RANS simulation can be started in a equally automatized way in order to get the desired output, thus feeding the single or multi-objective optimization solver that will give a new set of shape

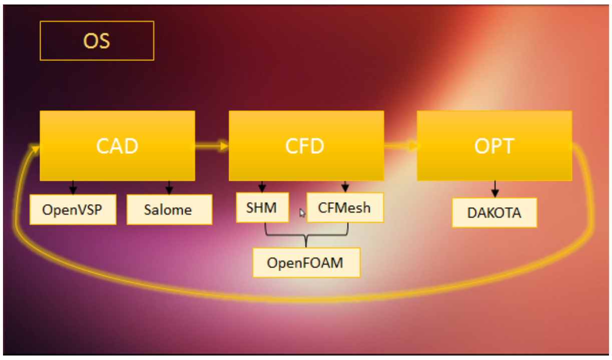


Figure 2: Workflow of free parameter-based optimization

parameters (e.g. Figure 3).

For the sailing appendages we use *Open Vehicle Sketch Pad*, an open source parametric aircraft geometry tool released by NASA in 2012 [5]. OpenVSP GUI allows the user to create a 3D model of an aircraft defined by common engineering parameters while the same can be exported and processed into formats suitable for engineering analysis. The applications allows also to select all the variables in a proper file. The base geometry shape can then be modified by separately change the values in the design file and run it in batch mode with a single line command. For the hull geometry parametrization, instead, a python script running in SALOME batch mode was created. This code uses SALOME geometric 2D and 3D functions in order to deal with complex features and to generate the smooth coordinates transform needed during the optimization.

Mesh generation was accomplished with *CFMesh* for the dagger, keel, bulb and rigid wing examples, while for the more complex Free-Surface VOF simulations a customised utility interface has been created in order to easily use *SnappyHexMesh*. The base mesh it has been chosen to be hexahedral due to the straight direction of the incoming flow. It can be stated that the calculated information follow one preferable direction in a vast majority of cells hence a regular mesh is suitable. Obviously the domain has been refined

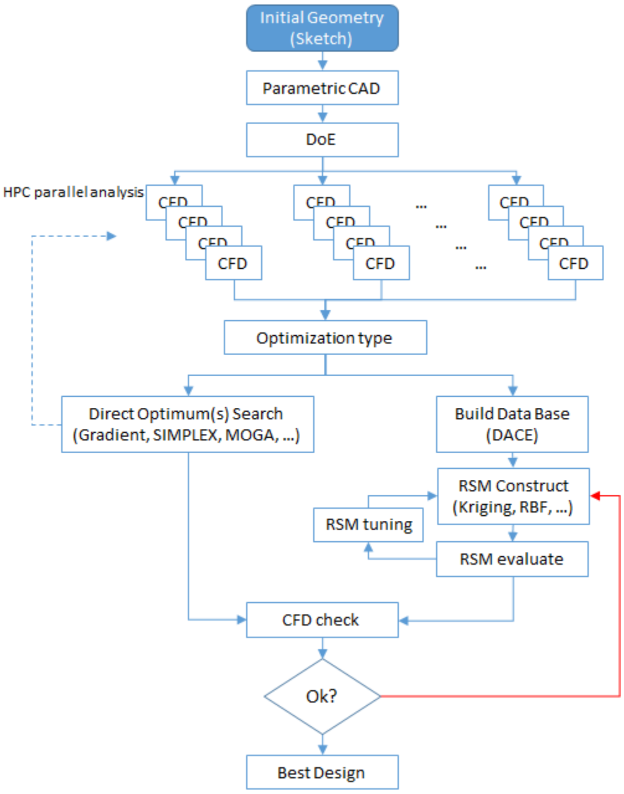


Figure 3: Workflow of free parameter-based optimization

in the proximity of the body where the quantities variations are important.The physical condition of the sailing yacht appendages has been considered stationary since a time average of the torces and the torques on the body was the objective of the study. The solver selected is simpleFoam and the convergence criteria has been imposed on the pressure and the velocity residuals (respectively 10^{-6} e 10^{-7}). Implicit unsteady VOF interface solver, interFoam, has been selected for the hull resistance prediction. Another important consideration must be set for the type of optimization that would like to be done, e.g. see Figure 3. If the naval architect wish to explore different design options, a complete Design and Analysis of Computer Experiments (DACE) is foreseen. In this case we used the Surfpack package of DAKOTA allows a series of Meta-Models that can approximate the Response behaviour of our geometry system based on the Space Exploration just done. This technique it is extremely useful when many runs are needed but the cost of a single run is very high. When instead the designer wish to increase the performance of an already existing design or ha has enough experiments as starting point (DoE), a single, or multi-objective, optimization can be directly performed using Gradient, SIMPLEX or Genetic Algorithm.

3 CASE 1: Daggerboard

The dagger-board is a sailing yacht appendage used to balance part of the side force coming from the aerodynamic pressure developed on the sails. The shape is wing-like and can be slightly curved in order to gain some vertical lift and/or perform better at heeling angles different from the design one. An example of different dagger geometry coming from the Design Space Evaluation can be seen in Figure 4. The information calculated by the simulations (pressures and velocities) can be directly connected to the static balance of the body, considering the facts that the position of the dagger-board is fixed and its weight variation is negligible. Hence a direct objective evaluation is possible and a multidisciplinary approach, concerning also structures and hull dynamic, can therefore be left aside for a stationary case.

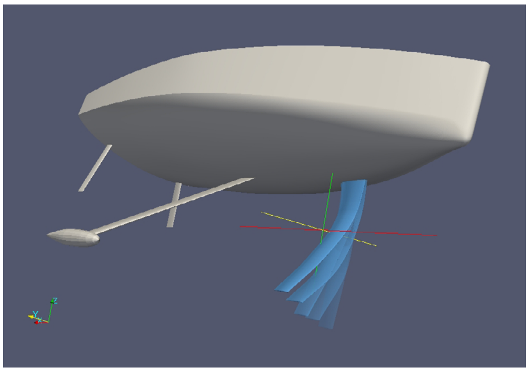


Figure 4: Dagger-board variation

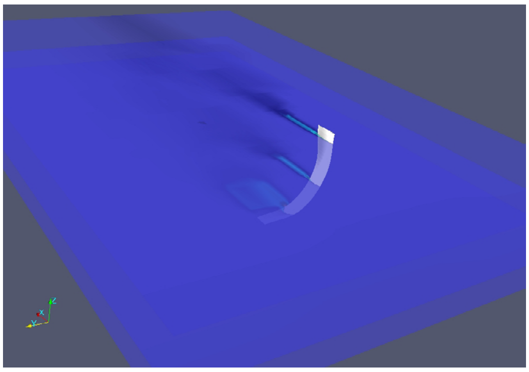


Figure 5: ν_t field at different vertical sections

The daggerboard is usually used in upwind course, leading to an average velocity basically in a complete turbulent regime ($Re > 10^6$). Therefore it has been chosen the $k - \omega SST$ turbulent model that has good characteristics for external flow. The dimensionless turbulent distance from the wall has been considered in the fully turbulent layer, $30 < y^+ < 100$, so that the logarithmic law is used and a low number of cell is ensured. The initial values of turbulent kinetic energy and the specific rate of dissipation were selected according to the equations detailed in Guerrero et al.[8] and a set of 10 simulations with very different daggerboard designs it has been tested before launching the Optimization. The calculated quantities respect the boundary conditions (in the Figure 5 only the turbulent viscosity is showed for sake of space) and the overall wall distance is more or less ensured all over the domain.
The wing-like geometry has been basically divided into two span-wise sections that combined for a total of 12 Variables. The Objectives of the study have been focused on minimizing the Hydrodynamic Drag and maximizing the eventual Vertical force coming from the different design. To be consistent with the requirements on the expected Heeling Moment, the Side Force of the dagger-board (i.e. the Hydrodynamic Lift) has been set to a minimum necessary value creating a Non-Linear Constraint for the entire Optimization process.

The relevant amount of variables needs a fair number optimization iterations. Both a direct Multi-Objective Genetic Algorithm (MOGA) and different size of Design Exploration along with Kringing Surrogate Models (DACE), for the estimation of Pareto Frontier, have been performed. The results in terms of Matrix Scatter Diagram can be seen in Figure 6 and 7) for different techniques. These diagrams are perfect for the evalua-

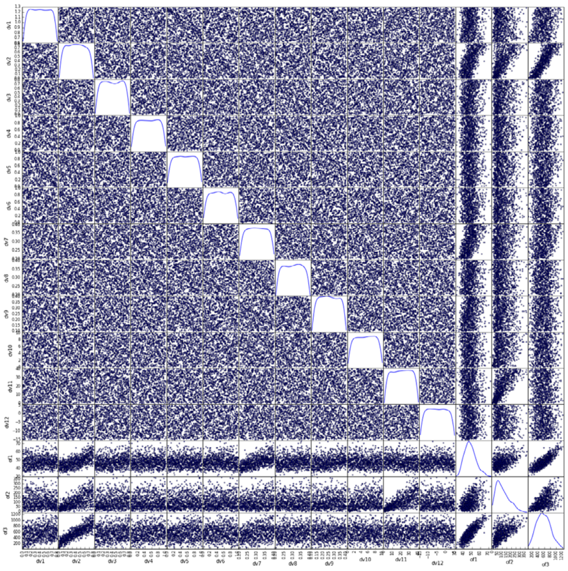


Figure 6: Matrix Plot of DACE

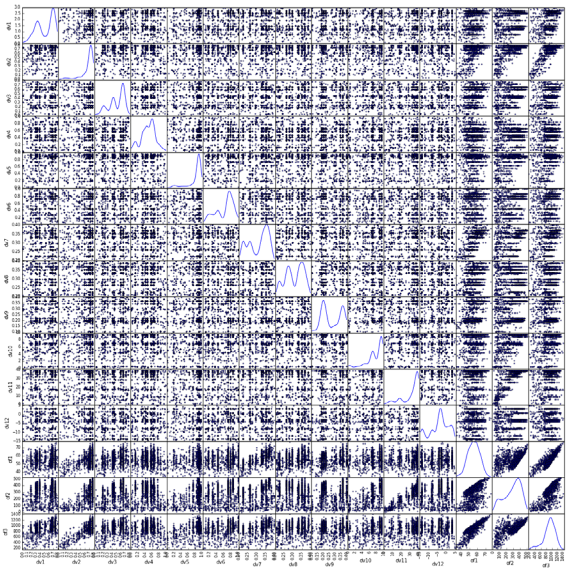


Figure 7: Matrix Plot of MOGA

Figure 8: Pearson’s Correlation Coefficient

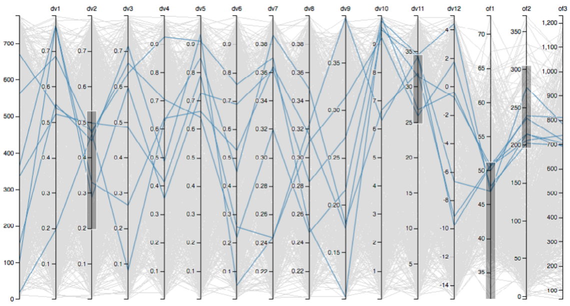


Figure 9: Interactive Coordinates Plot

tion of the variable space investigations and their distribution. From a first rapid look the most important influences and trends can be assessed and, then, further verified and/or intensified. Another important view if mostly interested on variable and function objects trends is the Pearson’s coefficient correlation (Figure 8) which can be combined with a matrix of gradient based cells. Nonetheless, an interactive Coordinates plot (Figure 9) has been coded such that the connection between single or multiple design parameter ranges with an objective area of interest can be seen. The objective functions domain can be seen in Figure 10 where the effectiveness of the non-linear constraint can be checked. In the end, the Pareto Forntier (Figure 11) can be showed for any different procedure analysed.

All the data analytics showed in this work have been post-processed trough free software as Python, Octave and the D3 Java dictionary. Beside the practical considerations that can be withdrawn in terms of advantages and drawback of the multiple optimum designs obtained, the entire work-flow from pre-processing to post-processing was absolutely enough to fully complete the complex engineering tasks foreseen.

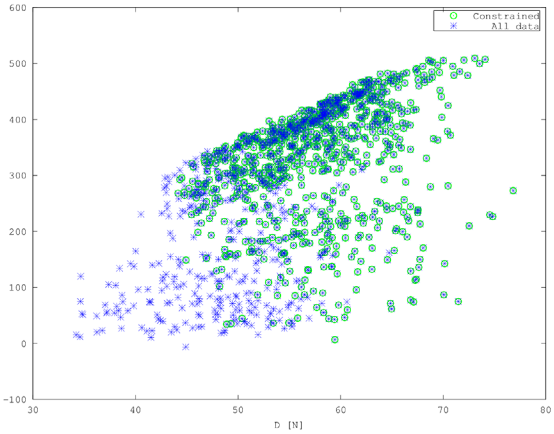


Figure 10: Non-Linear Constraint effect

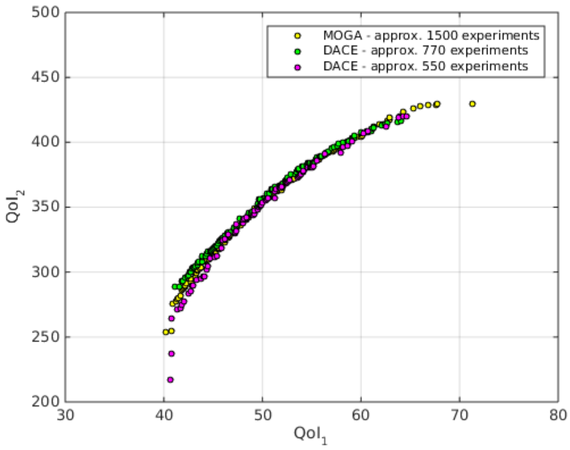
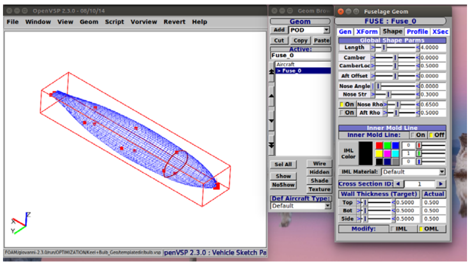


Figure 11: Pareto Frontier

4 CASE 2: BULB KEEL

A bulb keel is a keel, usually made with a high aspect ratio foil, that contains a ballast-filled bulb at the bottom, usually teardrop shaped. The purpose of the bulb keel is to place the ballast as low as possible, therefore gaining the maximum possible amount of leverage and thus the most righting moment. Since bulb keels work best on long, thin keels, they are generally not used on sailboats intended for shallow waters, but are most often found on offshore racing craft. Whilst the keel fin is strictly bonded by structural constraints and symmetry NACA profiles which optimization resembles the cases exposed in the previous sections, the bulb design presents a very interesting complex features and shapes (i.e. beaver tail, drop-like rounded body, occasionally with winglets). Moreover, even if the bulb Drag influences the overall resistance estimation, its Center of Gravity strongly affect the sailing yacht righting arm. These information can then be seen as natural objectives for a direct CFD optimization. Also for this case, we used *OpenVSP* with its *fuse02* module to define a bulb from its transverse sections (see Figure 12). Particularly, we designed the bulb such as the nose radius, the bottom tangents, its length, width, maximum width position, beaver tail vertical position could vary. Since we were starting the optimization from a valid geometry, the central sections where proportionally varied in terms of width and offset in order to not generate useless non conformal shapes which were out of interest for this case study. Some examples of initial DoE set for the analysis can bee seen in Figure 13, 14 and 15. The Pareto Frontier and matrix plots are not shown here for sake of space.



Add: POD
Active: Fuse_0
Aircraft
> Fuse_0
Def Aircraft Type: Default
FOAM/giovanni-2.3.0/run/OPTIMIZATION/Keel+Bulb_Geo/templatedir/bulb.vsp
penVSP 2.3.0 : Vehicle Sketch Pa

FUSE : Fuse_0
Length 4.0000
Camber 0.0000
CamberLoc 0.5000
Aft Offset 0.0000
Nose Angle 0.0000
Nose Str 0.3000
On Nose Rho 0.6500
On Aft Rho 0.5000
Inner Mold Line: On Off
IML Color 0 1 0
IML Material: Default
Cross Section ID: 1
Wall Thickness (Target) Actual
Top 0.5000 0.500
Bot 0.5000 0.500
Side 0.5000 0.500
Modify: IML OML

Figure 12: OpenVSP initial settings

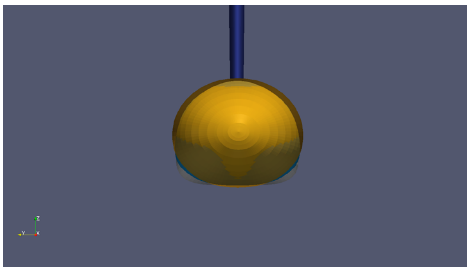


Figure 13: Front view of different Bulb

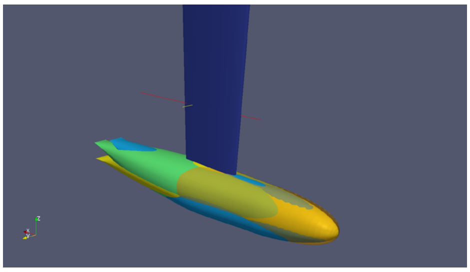


Figure 14: Lateral view of bulbs

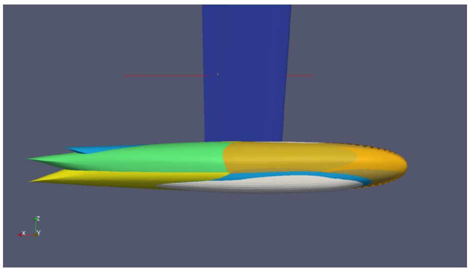


Figure 15: Bulb Keel isometric view

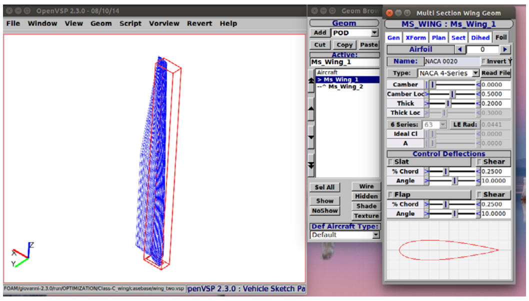
5 CASE 3: RIGID SAIL

In the recent years the search for light materials and better performances has brought the use of a rigid wing as sail. This solutions has become the peculiar part of the fastest sailing racers produced nowadays such as the AC72, AC45, Class-C and Class-A catamaran. From a design point of view, the use of rigid structure that sustains the aerodynamic loads strongly simplifies the rigging analysis and its optimization. In fact, for a soft sail design the Fluid Structure Interaction must be necessarily taken in account. Here, we used the Open-source Optimization Framework for the detailed definition of the VPP of a Class-C catamaran. In fact, the best sails settings for a complete parametric Polar Diagram can be obtained automatically by the definition of a wing geometry and wind profile. Giving the Optimizer the possibility to control the main sheet settings, the optimum solutions each True Wind Speed and Apparent Wind Angle it has been determined. For the downwind speeds as objective function we decided to maximize the Driving Force keeping while for the upwind we maximize the sail efficiency C_L/C_D keeping as constraint the Heeling Moment. The key part of the workflow in this case is to set the rear part of the sail in relative motion with the main front part which can be considered as absolute reference of the wing (e.g. see Figure 16). Fortunately, this can be automatically done inside OpenVSP where a little deformation of the front wing flap can also be evaluated for the CFD computations (even if not all the Class-C catamaran wing have this sail setting option). The possible sail settings are able to vary from the upwind to the downwind course as can be seen from Figures 17.

While the meshing strategy requires the same guidelines of the cases aforementioned, the physical model needs as inlet boundary condition the real True Wind Speed (TWS) profile which refers to the classical power law:

$$TWS(z) = U_{TW}\left(\frac{z}{z_{ref}}\right)^{\nabla a} \tag{1}$$

In OpenFOAM, fortunately, this boundary condition can be obtained via the *swak4Foam* Open-Source library. This library offers a number of utilities (for instance *funkySetFields* to set fields using expression), boundary conditions (*groovyBC* to specify arbitrary bound-



Airfoil 0

Name: NACA 0020

Type: NACA 4-Series

Camber 0.0000

Camber Loc 0.5000

Thick 0.2000

Thick Loc 0.3000

6 Series: 63 LE Rad: 0.0441

Ideal Cl 0.0000

A 0.0000

Slat

% Chord 0.2500

Angle 10.0000

Flap

% Chord 0.2500

Angle 10.0000

Figure 16: OpenVSP set for the Class-C wing

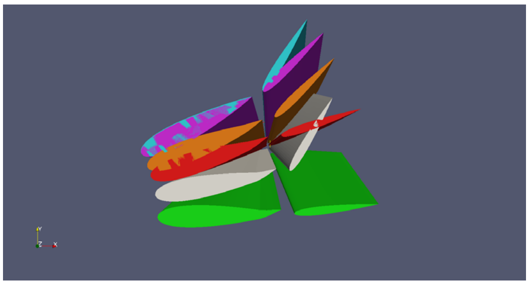


Figure 17: Variables exploration

ary conditions based on expressions) and function objects that allow doing many things that would otherwise require programming.

6 CASE 4: HULL

VOF model together with RANS implicit unsteady analysis is nowadays the industry standards for the CFD simulation of a generic hull. Particularly, the hydrodynamic behaviour along with the capturing of the sea free surface has become a key feature in a detailed design of racing sailing yachts. These simulations may take several hours on a simple workstations such that a design exploration of different geometries can be enabled by an HPC Cluster. Parallelizing different simulations runs on the same amount of cores is the leading edge technology used nowadays necessary to tackle overall complex engineering problems.
The CAD geometry has been generated using a python script in SALOME that starts from a cloud of coordinates representing a set of transverse sections from aft to fore and generate the complete hull with straight transom and deck. Having the three dimensional coordinates, the function(s) that creates geometry modifications are then decided BY the naval architect according his own ideas of optimization and personal know-how. In Figure 18, 19 and 20 an example of the hull solid generation and modification is shown. Particularly we decided to evaluate the influence of lateral chine in terms of position, number and height from aft to amidship considering to optimize the hull for the downwind performances (as Figure 21. In reality the heeled performance might be investigated too but the automatic mesh generations as described below must changed accordingly.

The mesh generation in these simulations needs a fair amount of attention due to the presence of a more or less complex shape (the hull) and an interface water/air which must be as sharper as possible. Phenomena like smearing or air entrainment lead to a wrong results and are basically related to a poor mesh quality.
Following the best practices used in marine applications and the experience with this kind of simulation of the writers, a newbie-user oriented script which runs an effective mesh generation automatically through OpenFOAM tools has been made. By inserting simple and well known quantities like the boat dimensions (LOA, BOA, height, Draft) and the velocity at which the simulation would like to be run, an hexaedral mesh useful for preliminary design can be obtained. The mesh created is also comprehensive of the

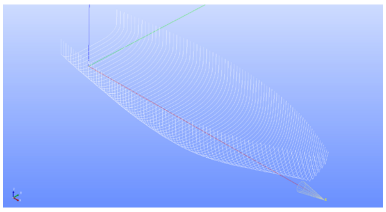


Figure 18: Hull sections import

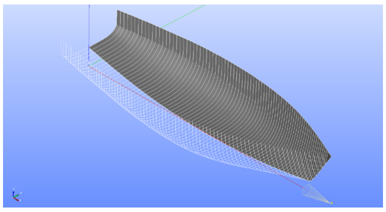


Figure 19: Loft and fill

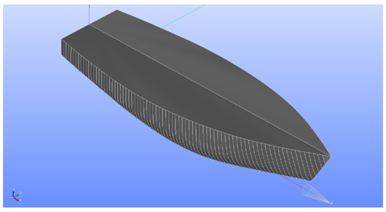


Figure 20: Final Solid

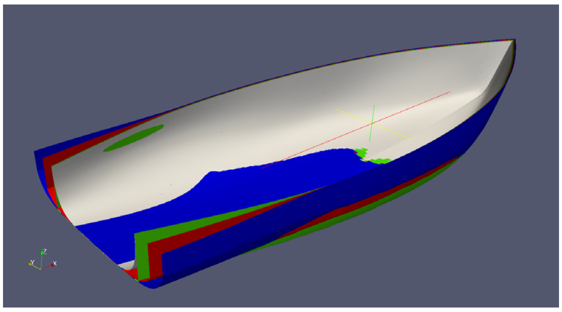


Figure 21: Aft parametric modifications

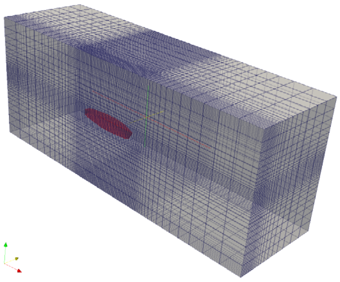


Figure 22: SnappyHexMesh automatic mesh

estimated boundary layer height at the wall. In few words, the surrounding domain is set with *BlockMesh*, then refinements regions (which level of refinement can be set by the user) are defined in the hull vicinity with *TopoSet* and the hull meshing is performed through *SnappyHesMesh*. The automatic mesh routine allows also the creation of a prism layer near the walls, necessary for the boundary layer approximations typical of the RANS code, asking in input the number and thickness of foreseen layers. A qualitative result can be seen in Figure 22. At the moment of the writing, this entire process doesn't scale very well and the limits is intrinsic to the SnappyHexMesh utility. Lately the authors put an effort in trying to reach the same mesh quality by using *CFMesh*. However, patches and boundary conditions come out already set during the mesh procedure.
Since the final objective of this case was to set a parametric hull optimization enabled on HPC systems for a preliminary design exploration, the rigid body is considered fixed. This assumption is necessary to still obtain a light mesh and smaller simulation times.

7 CONCLUSIONS

The major objective of this paper is the presentation of what can nowadays be done in terms of parametric CAD, RANS CFD simulations and multi-objective Optimization inside a completely Open-Source and Free Software environment. This procedure sees, in fact, the implementation of applications freely available. Tools like *OpenVSP*, *SALOME*, *CFMesh*, *SnappyHexMesh*, *OpenFOAM* and *DAKOTA* have proven to be effective both on a single workstation and on HPC clusters. The focus of the study has been set on racing sailing yacht design where the use of CFD simulations at different stage of the Naval Architecture spiral design is becoming more than an option.

In particular the Optimization Framework has been tested on:

- Daggerboard detail design using both DACE+RSM and MOGA Optimization philosphies;
- Bulb Keel exploration with non-derivative methods;
- Rigid sail/wing optimum setting for advanced and more reliable VPP formulation;

- Hull parametric design with multiphase implicit unsteady CFD.

The authors put their effort in this work trying to expand the tools that Naval Architects and Marine Engineers may explore and, eventually, use as cost effective solution for advanced and complex tasks.

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