

SIMULATION-DRIVEN DESIGN OF SAILING YACHTS AND MOTOR BOATS

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Abstract. The design of yachts and boats can significantly benefit from simulation-driven design (SDD) using codes of Computational Fluid Dynamics (CFD). In SDD a large number of virtual prototypes is investigated numerically for key objectives. In hydro- and aerodynamics objectives often relate to resistance and lift which govern the performance of both sailing yachts and fast motor boats. In order to reduce the dimensionality of the design space, i.e., the degrees-of-freedom, a parametric approach is utilized. For the flow simulation different levels of fidelity are used, ranging from potential flow analysis to viscous flow simulation solving the RANS equations. Design examples applying the SDD approach will be presented for both a sailing yacht and a motor boat. The sailing yacht is a 20m catamaran for worldwide travel and the motor boat is a 6m planing boat for day cruises. Parametric models for the two vessels will be discussed, comprising the generation of surfaces and watertight tri-meshes, the latter of which can be fed to the CFD code of choice. Here SHIPFLOW[®] and FINE[™]/Marine were applied in connection with CAESES[®] which provided both the shapes and the integration of CFD for SDD. To close the simulation driven design cycle of the sailing catamaran an appended version of the parametric model with rudders and daggerboard is used for virtual tank testing. Combining these results with a suitable sail model allows for an accurate velocity prediction (VPP) in an early design stage.

1 Introduction

While CFD ship hull improvements and optimizations are quite common for large commercial vessels, CFD driven design for saing yachts and small motor boats is usually limited to multi-million dollar projects such as the America's Cup. Costs are assumed to be prohibitive and incentives are missing. Fuel consumption is not an issue for pleasure boats and sailing performance is attributed to a "heavy" design or to the lack of abilities of the skipper. However, recent developments in parametric design of ship hulls and affordable CFD computations have changed the playing field. In this paper the investigation of a new design of a 20m sailing multihull (Fig. 1) is presented and the classic Riva Junior fast planing craft is revisited. Both designs have

in common that they use a hard chined hull. Nevertheless, the methods discussed can be readily applied to round-bilge hulls as well.

For the sailing catamaran hard chines were chosen for easy manufacturing in aluminium based on developable surfaces. It is shown that a systematic variation of the hull parameters leads to a significant reduction of total resistance compared to a manually lofted hull. After defining the optimization goal, a fully parametric model is developed for the canoe body of a single hull using CAESSES[®]. For the design selection a multiple stage approach was taken: 4508 models were investigated using the potential flow code of SHIPFLOW[®] for wave resistance. Subsequently, the most promising parameter ranges were chosen to analyse 521 models with regard to their total resistance using SHIPFLOW[®]'s zonal approach which combines a potential flow solution for the wave resistance with a viscous resistance solution for the rear half of the hull and the wake. The best design was selected and verified by comparing the resistance curves for the whole operating range using both FLOWTECH's SHIPFLOW[®] and NUMECA's FINE[™]/Marine. The parametric model then is refined to include two hulls as well as rudders and daggerboards. This model is used to find a suitable distance between the hulls and to generate virtual tank testing inputs for a velocity prediction program (VPP) under different sailing conditions using FINE[™]/Marine.

The example of the motor boat at planing speed presents an automatic minimization of resistance via a design-of-experiment (DoE) combined with a deterministic search. CAESSES[®] and FINE[™]/Marine were coupled as an integrated solution (Fig. 2). The example serves to highlight the procedure and the various elements involved – namely variable geometry, high-fidelity CFD and formal optimization – along with improvements that could be achieved.

2 Simulation-Driven Design of a sailing catamaran

2.1 Design Objectives

For motor driven vessels the design objectives are usually provided by the client in terms of pay load and velocity requirements. A sailing yacht, however, operates at an arbitrary number of load and velocity conditions which cannot be easily predicted. Therefore, for the load condition the worst case scenario of “fully loaded” was chosen at a displacement of 36t. Due to wave theory the total resistance vs. Froude number curve shows a certain “hump” at around $F_n = 0.3$. This hump can be seen in the resistance curve of the reference design. For the catamaran with a waterline length of 20 meters $F_n = 0.3$ translates into a boat speed of 8.2 knots. Apparently, the speed



Figure 1: DreamCatcherOne

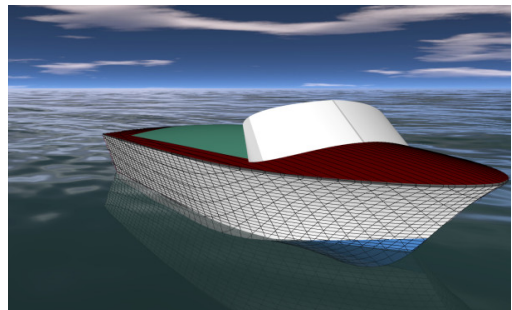


Figure 2: Fast motor boat modeled with CAESSES[®]

range between 8 and 10 knots should be within reach of a catamaran of this size even in light winds. Therefore, the reduction of this hump was chosen as the primary optimization goal. At the same time the optimization should not sacrifice the speed ability in normal wind conditions. From analytical estimates considering an upwind sail area of $270m^2$ the normal upwind ability results in around 12 to 13 knots. This leads to a two speeds optimization approach for $F_n = 0.3$ (8.2 knots) and $F_n = 0.44$ (12 knots). Consequently, all 4508 models were evaluated for these two speeds to select the designs with the best overall performance.

2.2 Parametric Models

The parametric models use three sections, an aft, a main and a bow section. A model with three plates and one with four plates below the waterline was developed to investigate whether a better approximation of an optimum elliptical shape by using more plates would lead to better designs. Both section models use given, but variable waterline and keel line curves as well as a flare angle and a dead rise angle curve over the complete hull length. This allows for a flexible positioning of the main sections. The three plate model further uses the sectional areas as input to generate the section.

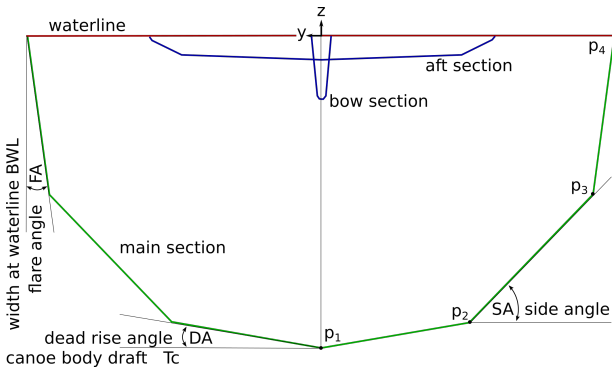


Figure 3: Three plate model: section geometry

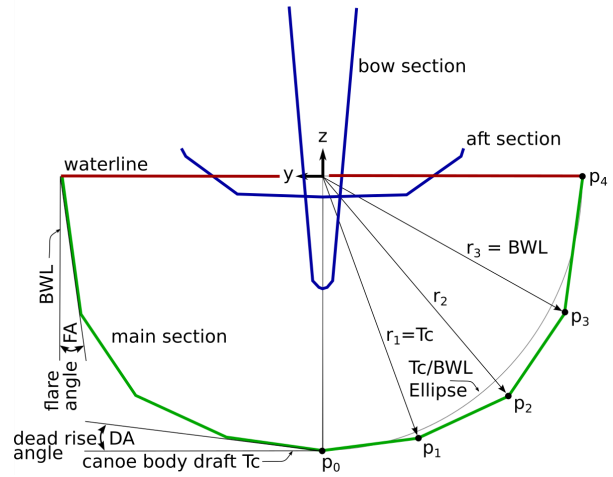


Figure 4: Four plate model: section geometry

For reduction of total resistance the wetted surface area needs to be considered as well. In the current approach the length of the section curve (length from $p_1-p_2-p_3-p_4$ in Fig. 3) was minimized using a quadratic equation to find the positions of points p_2 and p_3 in dependence of the sectional area, deadrise angle, the side angle and the flare angle. Using a Brent minimization approach within CAESSES[®] the side angle was varied to minimize the length $p_1-p_2-p_3-p_4$. The idea follows the assumption that if the curve lengths of the sections are minimal and the hard chines connecting the points among the aft, main and bow sections are fair, then the wetted area of the surfaces created between these hard chines is at least close to its minimum as well. Analysing the created models showed that the wetted surface area among all designs varied only by a maximum of 1.5%.

Many hand-made design variations suffer from varying displacement values [1]. In the current parametric approach the main section area is varied using a second optimization to meet the displacement of 18t per hull with a deviation of less than 0.1%. By keeping the displacement constant any variations in resistance can be directly attributed to the changes in the geometry.

The four plate model (Fig. 4) follows a similar approach whereby the geometry depends on $r_1 = T_c$, r_2 ,

$r_3 = BWL$ as well as dead rise and flare angle. The radius r_2 halves the angle between r_1 and r_3 and is chosen such that the length $p_0-p_1-p_2-p_3-p_4$ is reduced. The surface between p_3 and p_4 is extended linearly up to a further chine well above the waterline to avoid the introduction of an additional chine at the waterline. A hull generated using the four plate model is shown in Fig. 5. The waterline is marked in red.

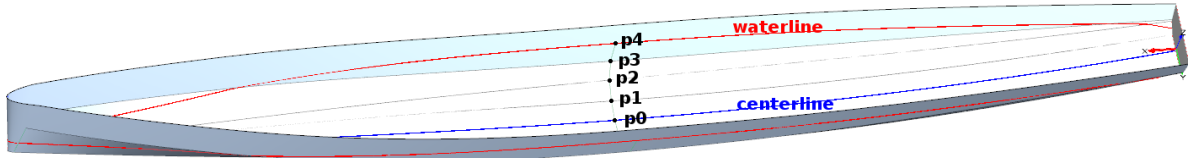


Figure 5: Full hull using the four plate model

The models comprise more than 20 parameters completely defining the hull's shape. Seven to eight of these parameters (depending on the model three vs. four plates) have been systematically varied while the remaining parameters were fixed to meaningful values determined in a preliminary evaluation phase. Compared to conventional spline-based approaches using an uncontrollable large number of vertices the number of parameters is very low, but still allows for a wide range of possible hull shapes. It should be mentioned that not all parameter combinations lead to valid hull shapes: Out of 6000 parameter combinations for the potential flow analysis only around 4500 resulted in a feasible hull shapes. The number of feasible designs within a parameter range is an indicator for the stability of the geometry of a parametric model. The larger the allowable range for each parameter and the more extreme the allowable parameter combinations are the more flexible the model is. This is particularly important if non-conventional hull shapes are of interest. It was found that the parameters for bow fineness and stern width showed highest sensitivity towards the optimization goals. It also seems that the alignment of the hard chines with the flow around the hull strongly influences the performance. This does not come as a big surprise. However, an alignment of the chines with the flow does not lend itself to easily accessible design parameters without violating the fairness of the lines. Therefore, only with a systematic search the most favourable designs could be found.

2.3 CFD Analysis

The main advantage of a parametric model created in CAESSES[®] is its universal applicability to different CFD codes such as SHIPFLOW[®] and FINE[™]/Marine. For SHIPFLOW[®] a station based geometry export was used while FINE[™]/Marine requires tessellations of the complete calculation domain in the form of multi-body STL files. These simulations can be highly automated. The simulation times vary greatly from around 30 minutes for a wave resistance calculation using SHIPFLOW[®]'s potential flow solver, via around 4 hours for SHIPFLOW[®]'s zonal approach, both on a conventional 3,5GHz 4 core PC with 16Gb RAM, all the way up to more than 30 hours on a 3.0GHz 8 core PC with 64Gb RAM for a viscous resistance calculation with a free surface of an appended two-hull configuration using FINE[™]/Marine.

For the selected designs their total resistance over the complete operation speed range was calculated to verify that the lower resistance at $F_n = 0.3$ is not penalized at other velocities. Fig. 6 shows that the resistance hump at $F_n = 0.3$ could be mostly eliminated without sacrificing performance at higher speeds. The four plate model even performs better at higher speeds than the reference design.

In table 1 the numerical result as well as some geometrical and hydrostatic parameters of the designs are summarized. The main objective of reducing the total resistance at $F_n = 0.3$ was well achieved. The best three plate design shows a total resistance reduced by 13.5%, the best four plate design shows a reduction of

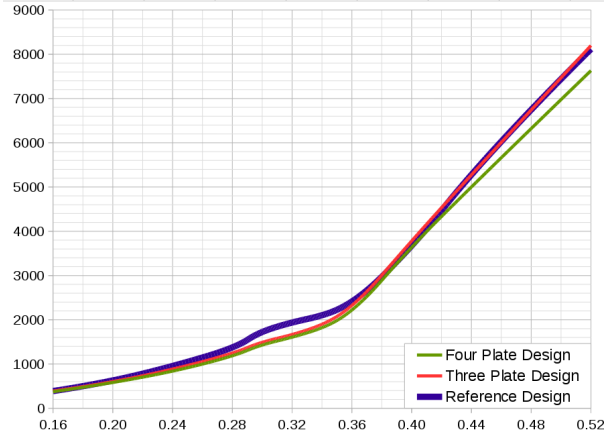


Figure 6: Total Resistance of the selected three and four plate designs compared to the reference design

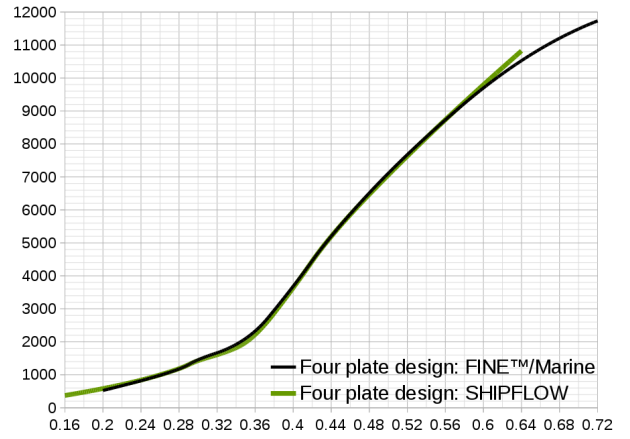


Figure 7: Total resistance of the four plate model evaluated with SHIPFLOW[®] and FINE[™]/Marine

17.1%. At the same time the performance at $F_n = 0.44$ did not suffer and even slightly decreased as well for the latter. Moreover, an interesting result is that beyond an L/B ratio of 10 it is not guaranteed that a larger L/B value stands for better performance. Figures 8 and 9 show the wave patterns of the best three and four plate designs compared to the reference design at $F_n = 0.3$ (8.2knots) and 0° heel. The improvements in the wave patterns show at the fore part of the hull and in the wave elimination in the wake.

Performance Parameters	Reference Design	Three Plate Design	Four Plate Design
$R_t(F_n = 0.3)$ [N]	1723	1490	1428
$R_t(F_n = 0.44)$ [N]	5277	5274	5195
Trim at $F_n = 0.44$ [$^\circ$]	0.82	0.83	0.86
Hull Parameters	Reference Design	Three Plate Design	Four Plate Design
LWL [m]	20.1	20.1	20.17
BWL [m]	1.60	1.90	1.84
T_c [m]	1.05	1.02	0.97
Wetted surface [m^2]	46.7	46.1	46.4
L/B	12.6	10.6	10.95
BTR	1.52	1.87	1.9
C_p	0.634	0.588	0.595

Table 1: Numerical CFD results and hull parameters of the demi-hull

In order to verify the validity of the results, the resistance curve of the best four plate design was re-evaluated with a different CFD code (NUMECA's FINE[™]/Marine) which uses a free-surface RANSE approach (Fig. 7). The maximum deviation between calculated values lies at $F_n = 0.36$ and reaches 5.5%, while at the optimization points $F_n = 0.3$ and $F_n = 0.44$ the deviation is 1.8% and 0.1%, respectively. Therefore, the optimization procedure can be assumed to deliver reliable results within an acceptable margin of error for a cruising catamaran. It is noted that the relative positioning of the different designs with regard to their performance is usually even more reliable than their absolute resistance value if the comparative evaluations are performed using the same mesh resolution and the same solver (as was done here).

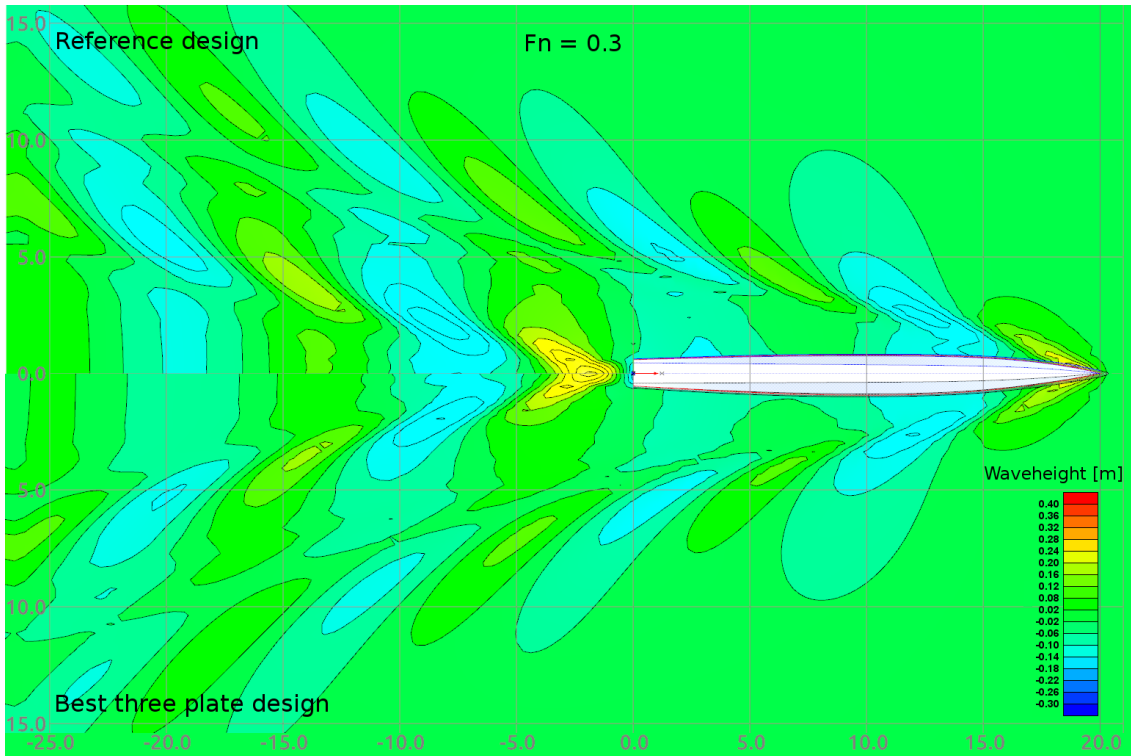


Figure 8: Demi-hull at $F_n = 0.3$: Reference design vs. best three plate design at 0° heel

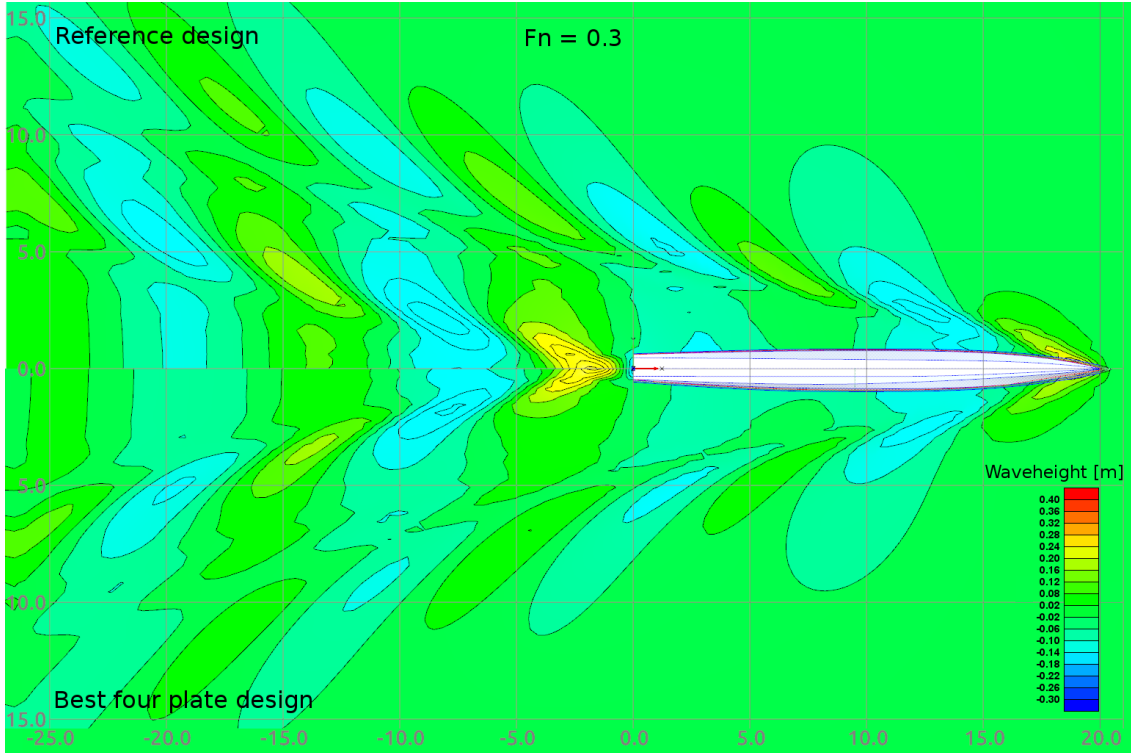


Figure 9: Demi-hull at $F_n = 0.3$: Reference design vs. best four plate design at 0° heel

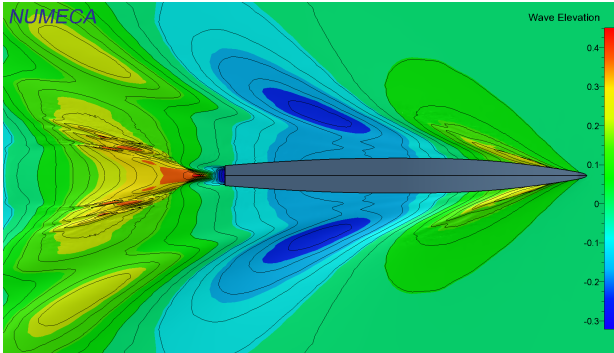
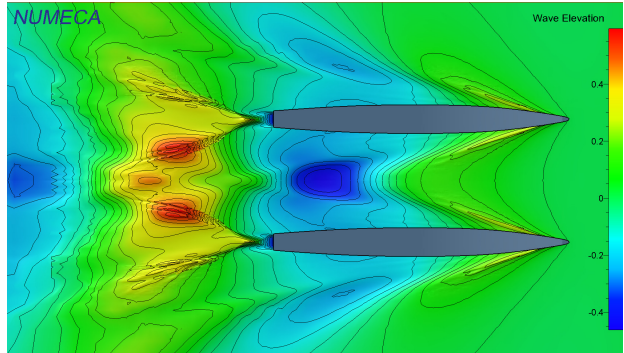
F_n	One hull	Two hulls catamaran configuration		
	Resistance [N]	BCB [m]	Resistance	Δ_R
0.3	2872	4.25	2908	1.3%
0.44	10568	4.00	12908	22.1%
0.44	10568	4.25	12506	18.3%
0.44	10568	4.50	12258	16.0%

Table 2: Resistance of one hull vs. two hulls catamaran configuration

2.4 Closing the design loop

A further advantage of a parametric model is the ability to re-use all the properties of the single hull canoe body model and refine it to include a double hull setup and appendages (rudders and daggerboards). Such a refined model is used to determine the best compromise between the hull's centerlines distance (BCB) and total resistance.

Table 2 shows the influence of a single hull compared to a two hull catamaran configuration. It can be seen that at $F_n = 0.3$ there is close to no interference between the hulls, while at $F_n = 0.44$ the hull interaction significantly increases the total resistance. The wave interaction for $F_n = 0.44$ is shown in figures 10 and 11. As expected, the data show that increasing BCB reduces the total resistance, but the effect slows down for larger BCBs. Therefore, a BCB of 4.25 meters was taken as a compromise.

Figure 10: Wave pattern at $F_n = 0.44$ one hullFigure 11: Wave pattern at $F_n = 0.44$ two hulls

For a preliminary performance prediction of the catamaran design the fully appended parametric model is used to generate the resistance data required for a velocity prediction program (VPP). Common VPP packages rely on hull data that is derived from the Delft systematic series with additions for heel and appendages. While this works satisfactorily for monohull designs with rounded sections, the data basis of the Delft series does not support hard chined multihull designs very well. Furthermore, sailing catamarans with daggerboards are normally sailed with the leeward daggerboard down only. This results in a highly asymmetric setup that is not easily accessible to analytical approaches.

This problem is overcome by calculating the resistance in the direction of movement and the sideforces generated by the hull and appendages for heel angles from 0° to 5° , leeway angles between 0° and 4° and for a velocity range between 4 and 14 knots. The limits were chosen in accordance with the anticipated operational profile. For example, the maximum heel was limited 5° since this represents the angle at which half the maximum static stability is reached. A cruising catamaran should not be sailed beyond this point for safety reasons.

With four points in each of these dimensions this approach leads to 64 calculations in total. Fig. 12

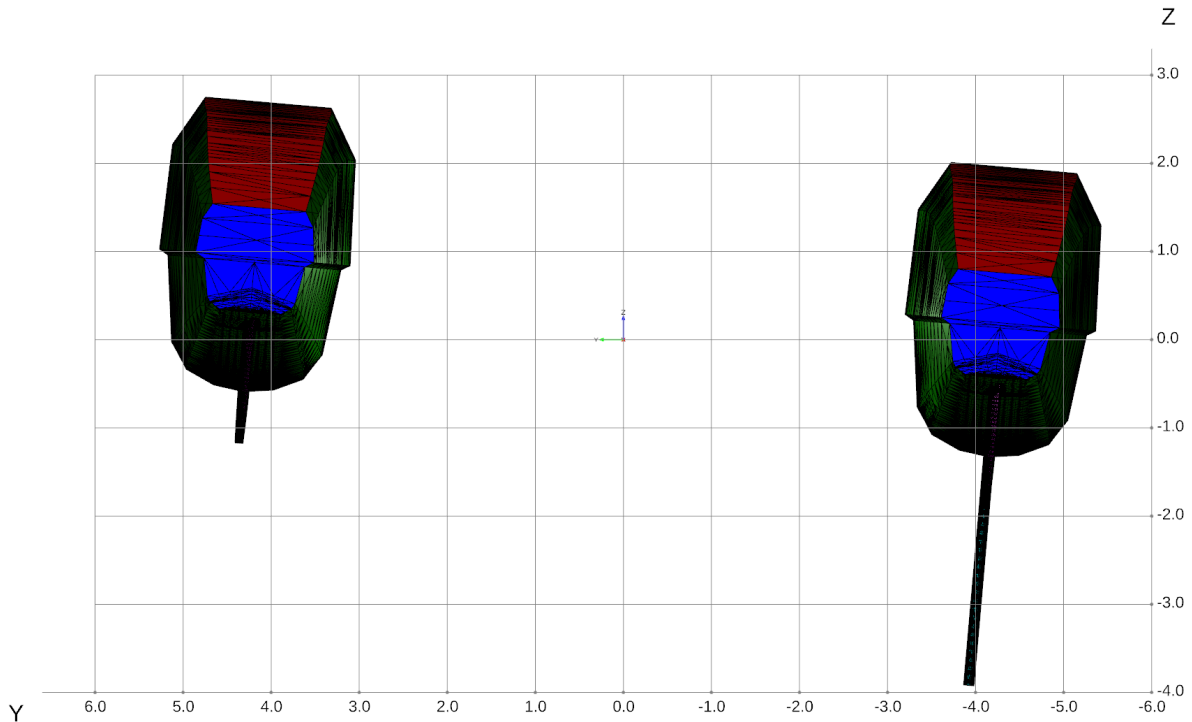


Figure 12: Water tight triangulation of the appended model

shows the watertight triangulation of the asymmetrically appended parametric hull model. The asymmetry requires a complete calculation domain of around 6 million cells. The calculations were performed on said 8 core PC. They took 77 days. Obviously this time frame needs to be reduced for every day use. However, high performance computer clusters with all the software required pre-installed are available for rent and can perform such calculations within a few days [5].

The resulting forces of the CFD calculations depend on the three independent variables heel angle, leeway angle and velocity. Fig. 13 and 14 show an example of the resistance and side forces for a fixed heel angle of 2.5° . For further processing in a VPP these values are interpolated using a spline based scattered data interpolation [2]. In previous work [3] Hazen's historic sail model is used to calculate the equilibrium of the hydrodynamic and the aerodynamic forces to derive the sailing performance under different sailing conditions. In the current case a more accurate sail model based on the ORC VPP aerodynamic model [4] is employed. Based on the CFD data and the aerodynamic model the expected sailing performance can be predicted accurately in an early design stage.

3 Simulation-Driven Design of a fast planing motor boat

3.1 Design Objective

A small hard-chine motor boat of around 6 m length and $1.3m^3$ displacement, typically used as a day cruiser on large lakes and as a tender for superyachts in coastal areas, was studied with regard to its performance at a design speed of 18 kn. With a Froude number of 1.32, based on the length of the design waterline at rest, this represents a planing hull for which dynamic trim and sinkage (or rather lift) and the influence of the free surface are crucial.

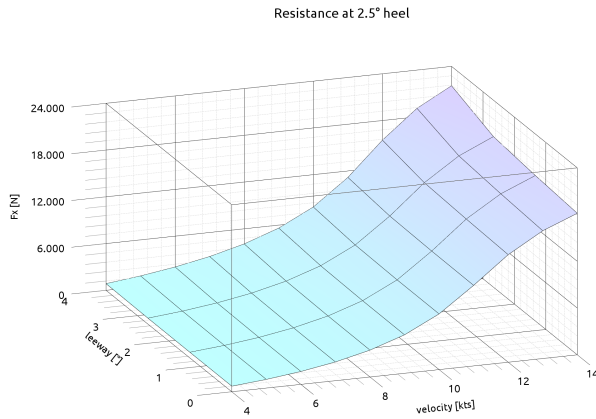


Figure 13: Resistance forces at heel = 2.5°

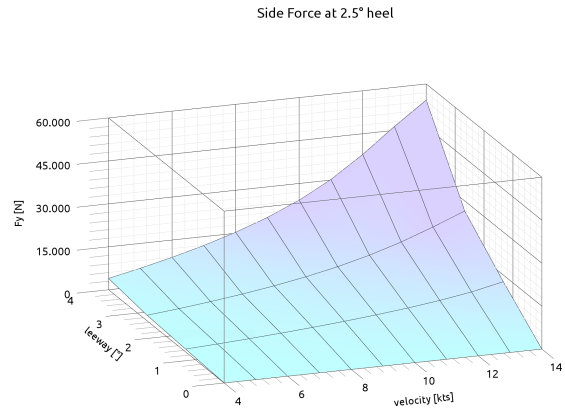


Figure 14: Side forces at heel = 2.5°

For this type of boats model test campaigns are often prohibitively expensive. A standard approach therefore is to rely on series data found in literature, see [6, 7]. Once the main particulars are set, the influence of small changes for the better or worse cannot be derived from the series data. Alternatively, a suitable parent hull is taken, slightly modified and subsequently built – naturally, hoping for reasonably good performance.

Both design approaches cannot provide answers to the typical design questions of how deadrise, rocker, hollowness of the planing surface, its warp towards the transom, width and shape of the spray rail and other design parameters should be chosen. In this situation an extended investigation based on simulation-driven design can help. To this effect, the geometry of the motor boat was parametrically modeled within CAESSES® while the flow was computed with the high-fidelity code FINE™/Marine, coupled to CAESSES® to be automatically executed in a design loop.

3.2 Parametric Model

As it is common in design work, an attractive and relevant baseline was chosen as a good starting point. Here the Riva Junior, a motor boat of classic beauty from the mid 1960s, was selected. A fully-parametric model was developed within CAESSES® [8]. For the purpose of the study the parametric model was built to support wide changes to the hull while being able to closely approximate the baseline.

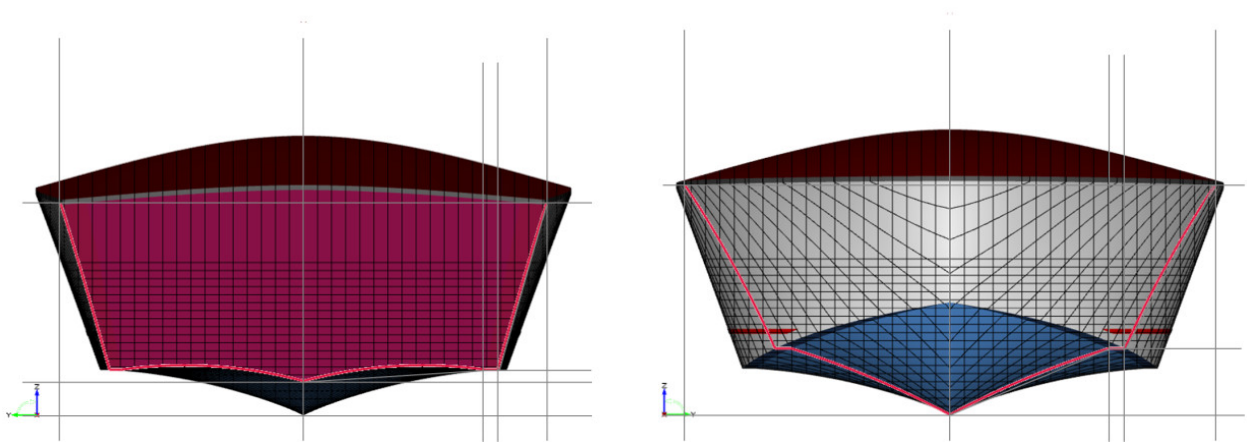


Figure 15: Building pattern of the generic section (left: section in the aft body, right: section in the forebody)

Similar to the parametrization of the sailing yacht as shown in figures 3 and 4, a building pattern for a generic section is defined first, representing the shapes found from stem to stern. For the motor boat, this section features a curved portion from the keel line to the inner knuckle of the spray rail, a flat portion forming the spray rail itself and another curved portion from the outer knuckle of the spray rail up to the sheer. Fig. 15 illustrates the building pattern for the aft- and forebody, respectively. Note that the actual geometry of the two highlighted sections (shown in red in Fig. 15) differs while the topology remains the same. Longitudinal curves define the parametric input to the building pattern at each position.

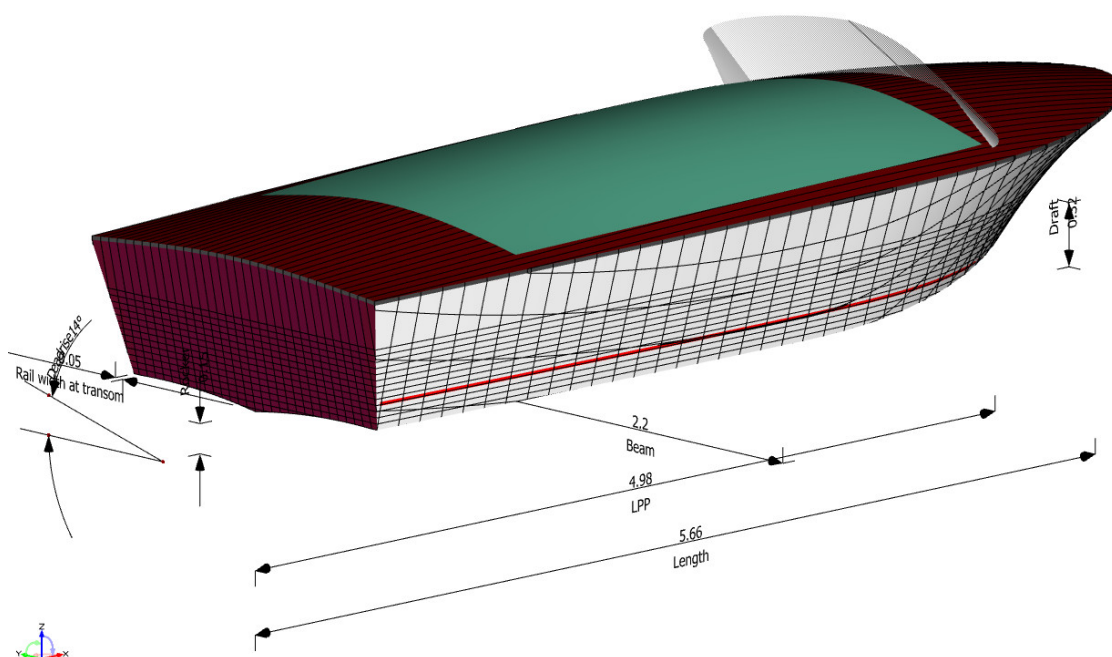


Figure 16: Selected parameters of the fully parametric model

Fig. 16 depicts important design parameters, namely beam, length (from the transom to the peak) and draft to define the main dimensions plus selected parameters for fine-tuning such as rocker (i.e., the rise of the keel line from maximum draft towards the transom stern), the width of the spray rail at the transom, the deadrise angle and the hollowness of the planing surface (i.e., its deviation from the straight connection from the keel to the spray rail). The parametric model is explained in detail in [5].

3.3 CFD analysis

Since viscous and free-surface effects both play important roles for fast planing hulls, FINETM/Marine was selected as a high-fidelity CFD code. The so-called “C-Wizard” by NUMECA was utilized which supports the user in selecting reliable settings for the simulation at hand. While CAESES[®] provides the boundaries of the flow domain including the hull itself in discretized form (via tri-meshes in STL-format), FINETM/Marine takes care of the grid generation (via HEXPRESS) and the actual flow analysis. Details of the pre-processing, the grid generation and the flow analysis are reported in [5].

During the simulations all boats were free to adjust to the equilibrium positions of the forces in longitu-

dinal and vertical direction and the moments about the transversal axis. The propulsion system, i.e., shaft, bracket, propeller and rudder, was not explicitly modeled but taken into consideration via a thrust force collinear with the inclined shaft line. The flow solver automatically balances the virtual thrust with the total resistance the vessel encounters, yielding the calm-water resistance at 18 kn.

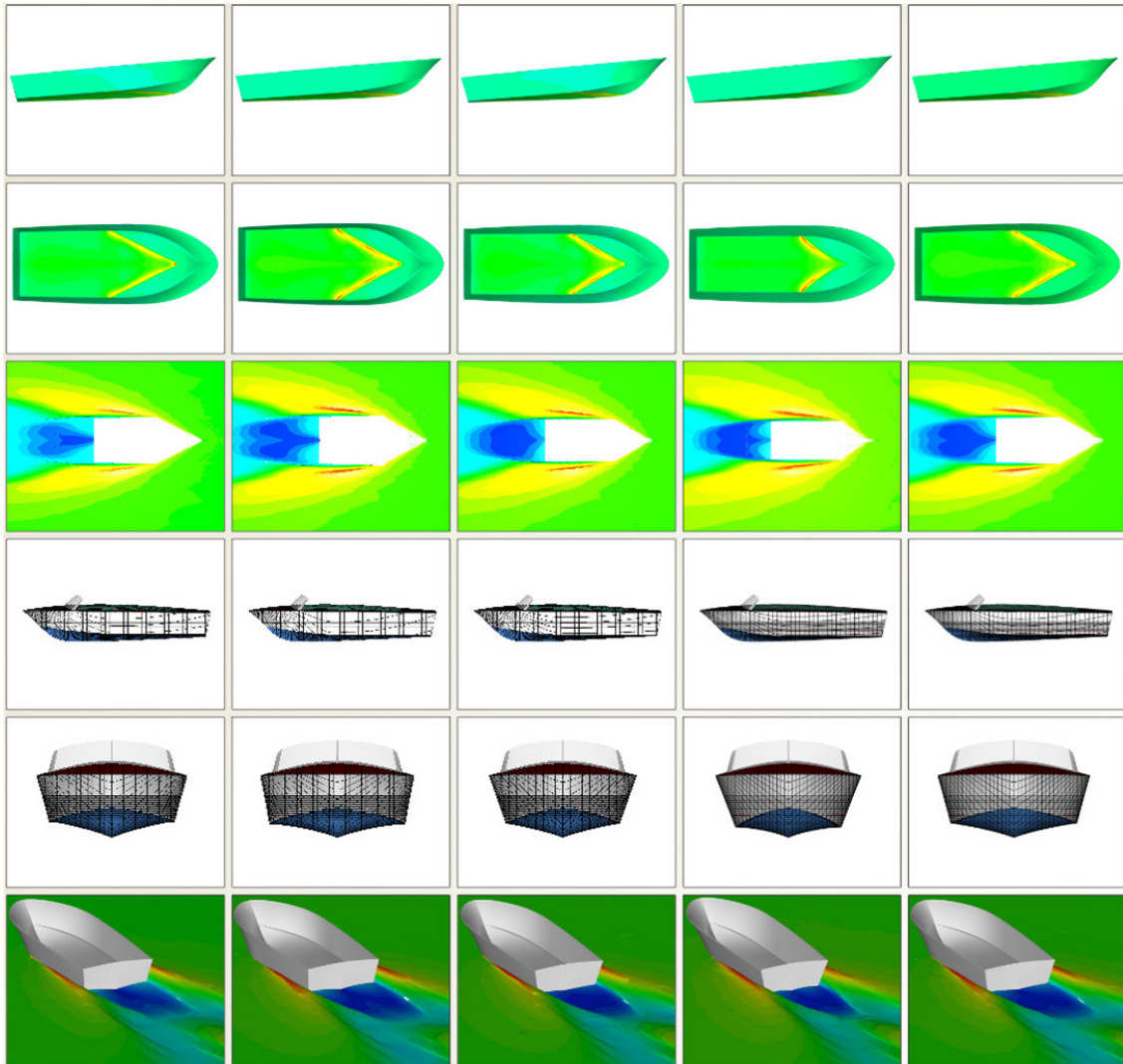


Figure 17: Designs investigated during the optimization (excerpt)

3.4 Closing the design loop

The advantage of investigating a large set of similar designs over modeling and analyzing just one single design (or one design plus a handful of variants) is to substantially increase the probability of identifying a highly effective design. Furthermore, it allows to study the cause-and-effect of geometry on flow fields.

Rather than undertaking the tedious work of remodeling, ex- and importing files, generating meshes, running the CFD analysis and producing plots and diagrams for many designs manually, a closed design loop is called for that, once established, runs these steps automatically. Similar to what was reported above for the sailing yacht, CAESSES[®] was employed to run a design-of-experiment, comprising 100 variants, and

several additional searches, for instance via a T-search which is a deterministic gradient-free search strategy.

Fig. 17 illustrates selected results taken from the large set of designs. It is an excerpt of five arbitrary designs for which trim (top row), pressure distribution on the planing surface (second row), the wave field in top view (third row), the actual geometry (fourth and fifth row) and the wave field in perspective view (final row) are shown – all of which were generated automatically and in exactly the same way, avoiding errors often found in manual processes.

From the many variants a particular effective design was found, namely a design which features 7% less resistance than the baseline, i.e., a reduction from 1572 N to 1461 N at 18 kn. Taking into consideration that the baseline was carefully designed already, this can be regarded as a significant improvement.

4 Conclusions

It was shown that simulation-driven design using fully parametric models leads to more effective yacht and boat designs. The effort is significantly reduced by automating the simulation procedure. CAESES® multiple interfaces to different CFD programs leaves the choice of the most suitable CFD solver to the user and even allows for effortless switching between CFD packages. Fully automatic identification of a design from a multi-dimensional design space always is a challenge because the parameter-to-objective relationships are often complex. Looking at many variants certainly helps to develop a good appreciation of possible compromises and gains. Whenever performance is critical, like velocity-made-good for a sailing yacht, speed attainable for a motor boat or even cruising range for a battery powered craft, a design largely benefits from more a effective hull.

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