Coupling of Aero- and Hydrodynamic Simulation for Racing Yacht Performance Optimization

Karsten Hochkirch

FRIENDSHIP SYSTEMS GmbH
www.FRIENDSHIP-SYSTEMS.com

Heikki Hansen

Yacht Research Unit, The University of Auckland
www.auckland.ac.nz

Summary:

Modern sailing yachts are complex systems operating at the phase border between water and air. Attempts to optimize the performance requires methods to evaluate the interaction of aero- and hydrodynamic forces and find conditions where the external forces are in equilibrium.

An outline of today tools to handle these problems is given and a new approach for effective optimization of such complex systems by means of parametric modeling is discussed. An example for the optimization of a 10m yacht using different objective functions is presented.

Keywords:

sailing yacht, optimization, velocity prediction, simulation, hydrodynamics, aerodynamics, interaction, wind tunnel

1 Introduction

Sailing yachts operate at the phase border of water and air and thus the interaction of hydrodynamic and aerodynamic characteristics is of utmost importance, Figure 1. Already in 1901 the famous German yacht designer Max Oertz [1] compared a sailing yacht to a gliding bird whose one wing operates in water and the other in air. Hydrodynamic and aerodynamic analyses are therefore only meaningful if the interaction of both is taken into consideration.

Figure 1 IAC Class yacht challenging for the Americas Cup in 2007

In the course of this paper an outline of performance prediction methods for modern yachts and a brief discussion on the numerical and experimental techniques involved are presented.
In more detail a new approach in hull form optimization by means of parametric modeling is introduced.

2 Sailing yacht performance prediction

The first important aspect of performance analysis for sailing yachts is the prediction of attainable speed for given wind conditions under steady state assumption. Following Newton's first law a steady state condition is achieved when all external forces acting on a body sum up to zero. Considering a yacht sailing on an upwind leg this in itself forms a nonlinear system of equations for the operating condition of the boat, i.e. boat speed (Vs), true wind speed (TWS), true wind angle (TWA), heel angle (ϕ) and leeway angle (λ) – just to mention the most important. Figure 2 shows the main components of hydro- and aerodynamic forces. Especially when looking at the total wind vector acting on the sails it becomes obvious that even a small change in boat speed will affect the apparent wind velocity as well as the apparent wind speed.

Considering the six degrees of freedom for a rigid body – depending on the type of boat – usually only four degrees are really computed, i.e. the trimming moment as well as changes of the vertical forces are usually not taken into account as their influence in considered to be of second order, however, more advanced method also handle full six degrees of freedom when searching for the equilibrium condition, see [2].

Due to the rather complex interactions of the total system and the different tools available for simulation of the physical flow properties the performance prediction is usually made up by two distinct steps:

1. Detailed separated analysis of the hydro- and aerodynamic components for selected steady state conditions. For instance, numerical analysis of the hull for a set of heel angles and forward speeds and setting up of a mathematical model from these results (response surfaces interpolating the computed or measured data for arbitrary conditions in between).
2. Once all models for all components are available the mathematical models are coupled and an equilibrium condition is solved for by conventional mathematical methods for the solution of the nonlinear set of equations.

However, considering the flexibility and complex control mechanisms of the aerodynamic part, i.e. rig and mast, it becomes obvious that the equilibrium condition is not unique and – as sailors usually do – the optimum of all possible conditions is searched for. A typical optimum is the one which yields maximum speed towards the finish line.
Often this is modeled by a set of trim parameters describing the crew's efforts to change the sail shape by a small set of numbers. These are then introduced as additional state variables (besides the rigid body motion).

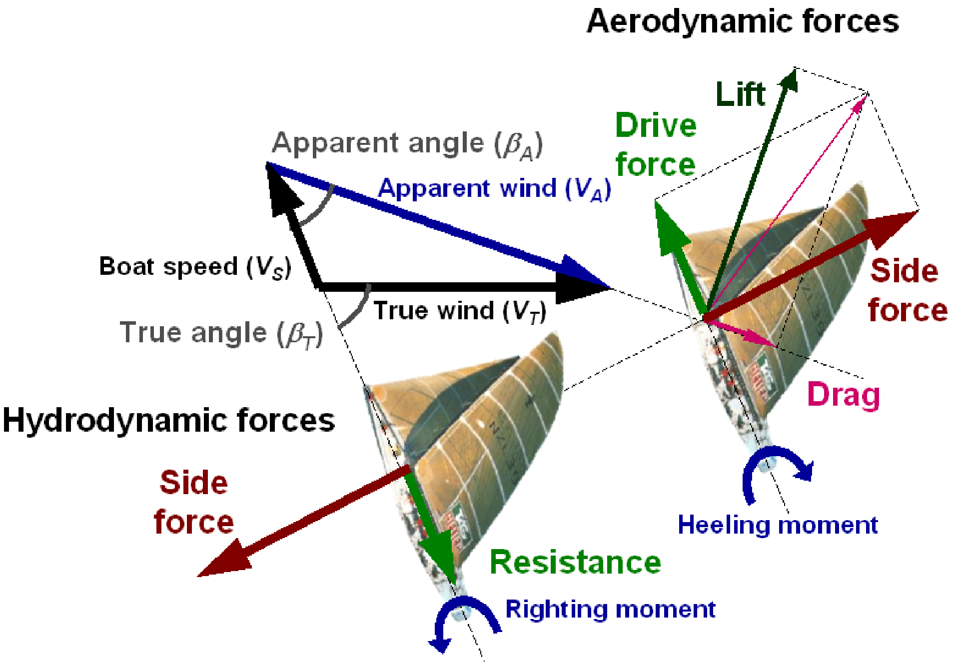


Figure 2 Principal forces acting on a yacht at an upwind tack

Furthermore, deformations of the sail shape due to the aerodynamic pressure introduce additional nonlinearities in the physical problem.

3 Aerodynamic models

In terms of fluid dynamics the aerodynamic part may be considered very challenging as – depending on the course of the boat – the rig operates under completely different conditions. While sailing upwind non-viscous methods may already be applied successfully to compute lift and induced while down wind sails definitely put high demands on viscous solvers for accurate prediction of forces. Here experimental methods such as model testing in a wind tunnel and full scale testing are still considered irreplaceable. Figure 3 shows large areas of separated flow on low-pressure side of spinnaker that need to be modeled correctly in wind tunnel testing and CFD simulations to obtain accurate force predictions.

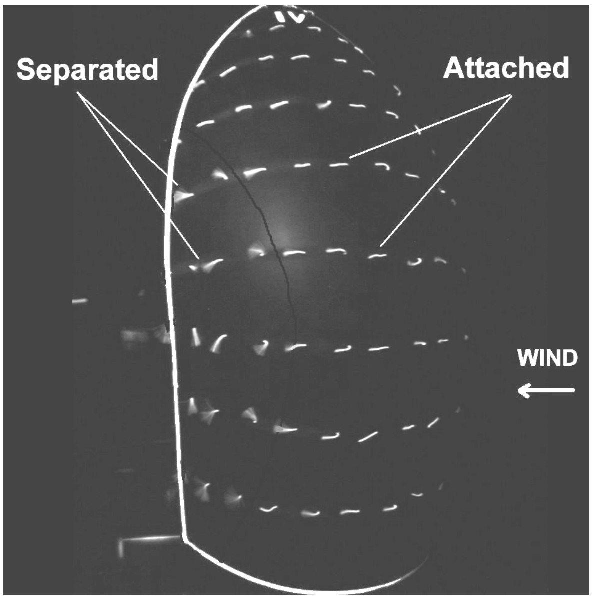


Figure 3 Off-wind sail with large separation visualized in a wind tunnel test with cotton tufts

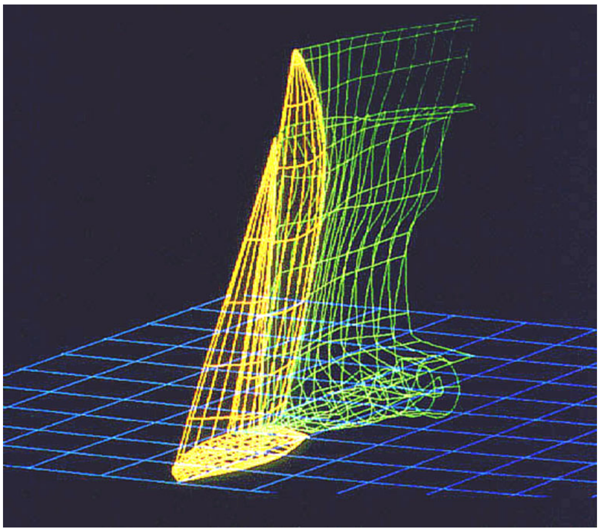


Figure 4 Vortex lattice computation for an upwind sail configuration with wake relaxation

However, the model testing for sails is not as straight forward (when compared to hydrodynamics) since strong interactions between various physical relations exist which cannot be modeled in the wind tunnel easily. These include Reynolds number effects, modulus and elasticity of the sail fabric plus a rather complicated geometry (if shrouds, stays, etc. are considered).

For upwind sails where separation is limited to small regions potential flow codes give good results with a very short response time Figure 4. For very detailed investigations, however, also RANS codes are employed such as displayed in Figure 5 which depicts a result of a trim variation analysis for an 10m IMS cruiser racer from [3]. Usually even the response time of non-viscous codes does not allow using them directly while solving the coupled equations. Therefore systematic variations are carried out and a regression function is identified which is used in the velocity prediction, see Figure 6. The parametric description of force changes due to trimming is however very complex since the flying shape of flexible membrane sails depends on a large number of variables and defining appropriate regression functions is not trivial.

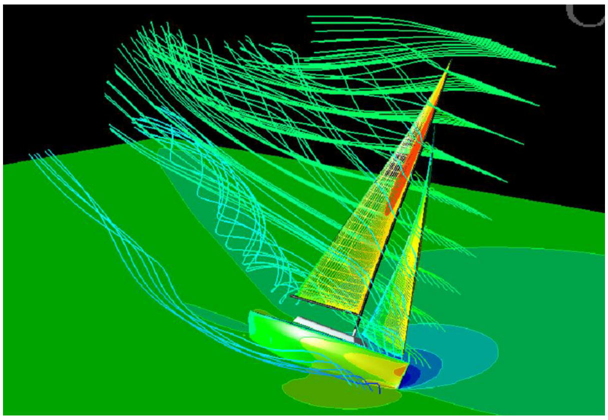


Figure 5 Stream lines and pressure distribution as calculated by [3]

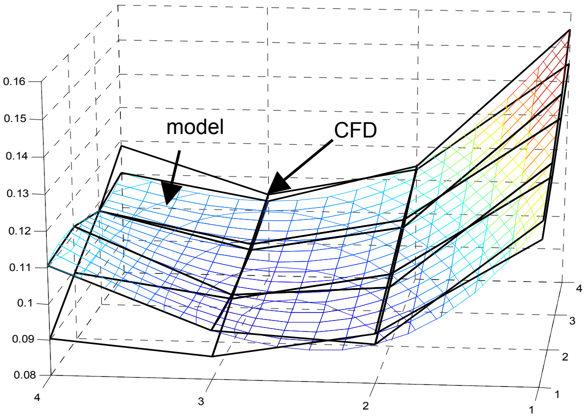


Figure 6 Computed CD and modeled values for trim optimization

Although in principle solving the complete setup, hull and rig including integration of motion, is possible within modern RANS codes, see [4], the required level of accuracy is not yet on a comparable basis in terms of computation time and economic aspects.

Of major interest are aero elastic interactions between fabric and aerodynamic loads since the actual flying shape of the sail may significantly differ from the 'design' shape as it comes from the sail maker's lofting program. Today many groups work on prediction of aero-elastic interactions. While tools for coupled aero- and structural analysis codes have become a standard for upwind sails, see [5], downwind conditions are still more confined to research applications, see for example [6].

Despite apparent scaling issues being unresolved, wind tunnel testing of downwind sails still seems to be the favored technique to distinguish between design alternatives – especially for off-wind sails – as most Volvo Ocean Race teams and a number of America's Cup syndicates conduct extensive testing sessions in the Twisted Flow Wind Tunnel at The University of Auckland, New Zealand.

4 Hydrodynamic models

The hydrodynamic forces acting on the underwater part of the hull are characterized by significant lift and induced drag forces which interact with the free water surface. Figure 7 shows a typical view of a sailing yacht sailing at a high Froude number. These interactions become more prominent for low aspect ratio underwater hulls as common to some traditional boat classes. The figure shows the nonlinear wave pattern on a dragon class hull.

The major source for the integral data for lift and resistance stems from model test results extrapolated via Froude hypothesis. However, especially for detailed analyses of individual parts the integral values are 'stripped' by the aid of theoretical formulations. Differences computed from CFD (RANS or potential flow) are applied to simulate, for example, a changed rudder configuration.

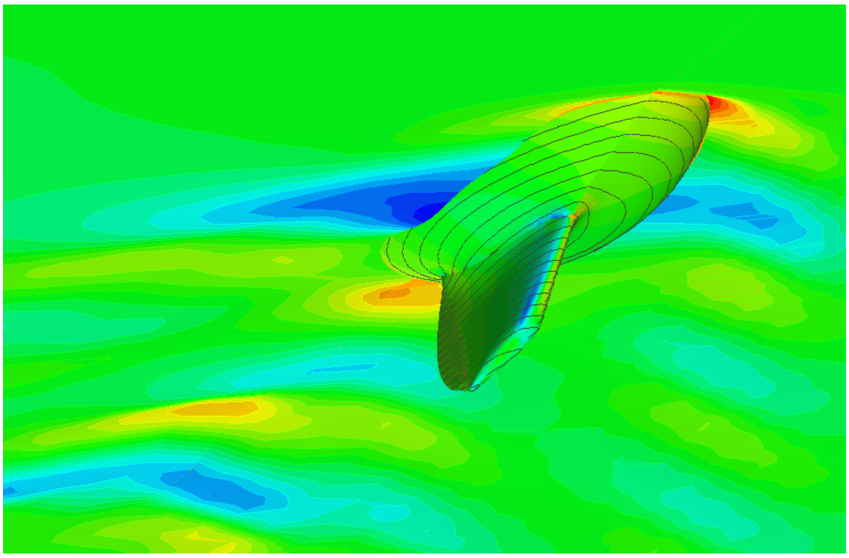


Figure 7 Nonlinear free surface flow computation for a dragon class hull

The common feeling nowadays is that model testing techniques for large scale models are mature and reliable. Therefore for ultimate quantitative analysis model test data are first choice if the budget and time is available. Numerical codes become more favored for computing differences between design alternatives but still input parameters (i.e. turbulence intensity) are ‘calibrated’ to match the measured values.

5 Velocity prediction

Once the models for aero- and hydrodynamic forces are formulated they are integrated into a velocity prediction program. Due to the variety of different force models FRIENDSHIP SYSTEMS has developed a flexible workbench to integrate a wide range of different force models in a unified manner, see Figure 8. Different solution techniques are then available to find the equilibrium condition or simulate the rigid body motion of the yacht when integrating the excess forces using Newtons second law.

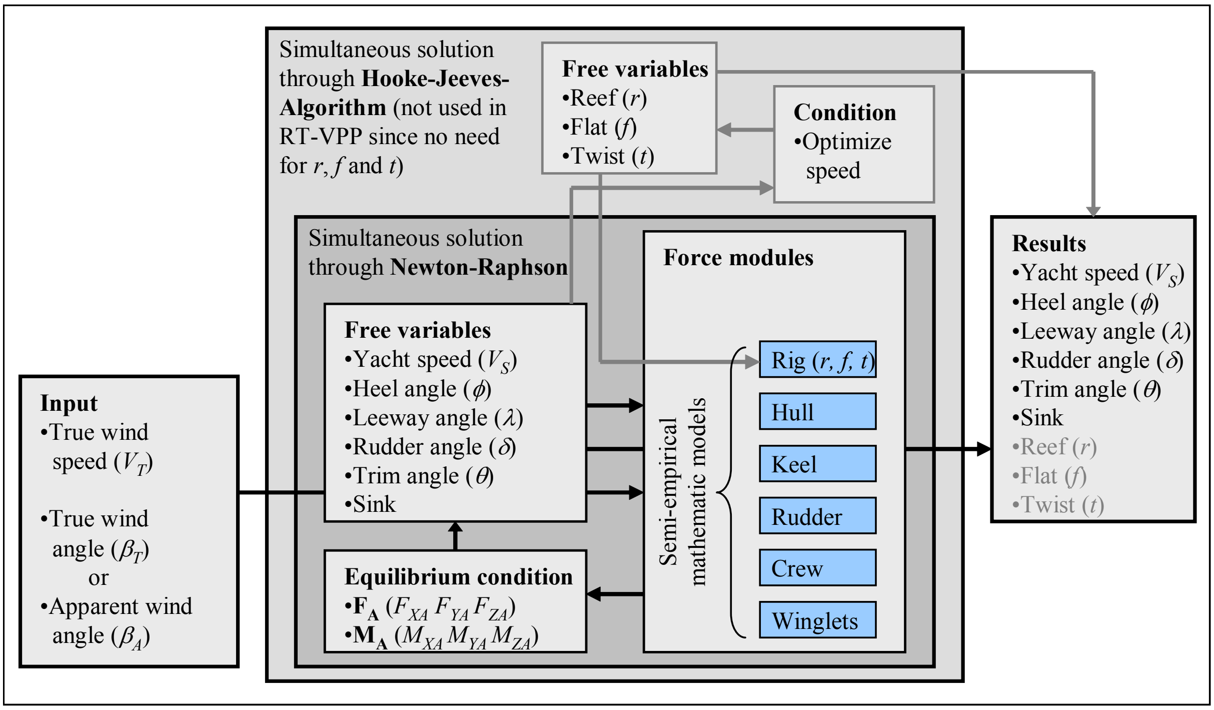


Figure 8 Principal setup of the modular velocity prediction program FRIENDSHIP-Equilibrium

Figure 9 Scale model of a 10m IMS cruiser racer yacht in the Twisted Flow Wind Tunnel

Figure 10 Inside of a wind tunnel model showing remote control winches to trim sails as in real life

Due to the modular structure distinct modules can be selected for optimization and altered to accommodate the design changed to be investigated. The program will then compute the new equilibrium condition for different true wind speeds and thus provide the ultimate measure of merit – speed.

6 Experimental methods for coupling

Especially when designing and testing sails for a specific yacht it is of significant advantage to have a fast response on the influence of trimming on the boat speed. Advanced wind tunnel testing methods developed by The University of Auckland and FRIENDSHIP SYSTEMS include numerically modeling the hydrodynamic forces corresponding to the current measured aerodynamic forces. Figure 9 and Figure 10 show the setup used in the Twisted Flow Wind tunnel at The University of Auckland: The measured forces are transferred by the online data acquisition system to FRIENDSHIP-Equilibrium acting as velocity prediction program and computing the hydrodynamic state condition required to balance the aerodynamic forces. This enables designers and sailors to trim the sails to optimize boat speed as they would in real life on the water and thereby reducing the dependency on parametric regression while achieving a fast response time. In addition sails are now tested at the correct heel angle as the computed heel angle can be used to adjust the model in the wind tunnel accordingly, see Figure 11.

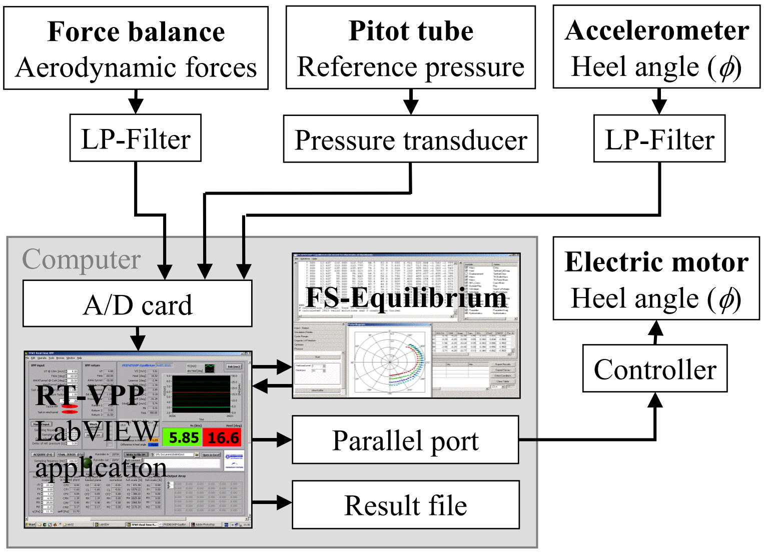
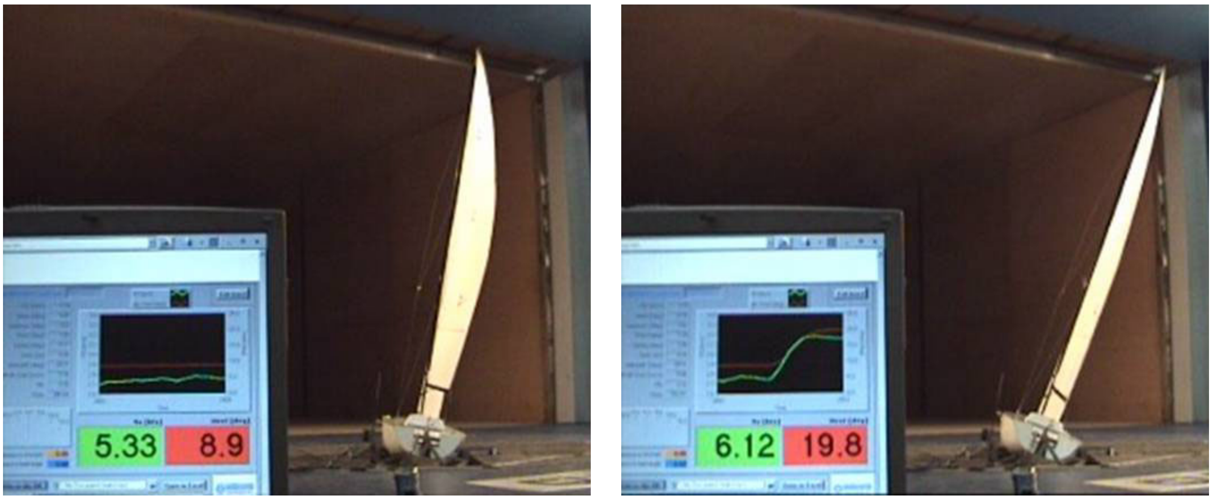


Figure 11 Schematic implementation diagram of the Real-Time VPP in the wind tunnel. This setup allows the sail designer to trim the sails much more efficiently in the wind tunnel



a: Model with sail twisted off, less Vs & ϕ

b: Model with sail fully powered up, more Vs & ϕ

Figure 12 The Real-Time VPP predictions (left value is Vs and right value is heel angle (ϕ)) for two sail trims to illustrate Real-Time VPP use as trimming aid

Figure 12 shows two different sail trims and corresponding boat speed and heel angle. For more details see [7].

7 Optimization

Optimization of a sailing yacht is thus a very complex undertaken and usually only one design detail is targeted at a time and just one operating condition, e.g. upwind at a certain wind speed is taken into account.

The following will describe an advanced technology of canoe body hull form optimization as it is applicable to sailing yachts. The canoe body itself plays a central role in the overall performance since it contributes a major part of the righting moment to balance the heeling moment produced by sails and hydrodynamic forces on keel and also operates at the free surface and thus produces the wave pattern contributing to the resistance of the boat.

FRIENDSHIP SYSTEMS has developed a unique parametric hull form design system. Within this system, the hull geometry is directly generated from a small set of form parameters, while the characteristics and constraints of the hull configuration are maintained and the shape is optimized with respect to fairness. The modeling approach is based on multiple nested optimizations of uniform B-spline curves defining sectional properties of the hull for each longitudinal position. These curves are built from a flexible selection of properties. For instance, the plan view of the deck can be specified by its forward end at the bow, the position of the maximum beam and aft end at the transom. Tangency and curvature conditions can be optionally applied. The modeling algorithm then arranges the controlling vertices in such a way that the specified properties are met while the curve is kept as fair as possible. Finally, the FRIENDSHIP-Modeler can be easily coupled to a hydrodynamic analysis chain including CFD predictions for wave making resistance, viscous resistance or other quantities of interest, see [8].

This process can be automated and a generic optimization toolkit such as the FRIENDSHIP-Optimizer can be used to adapt the input parameters to the hull to optimize for a certain objective function, e.g. velocity made good to windward, see Figure 13.

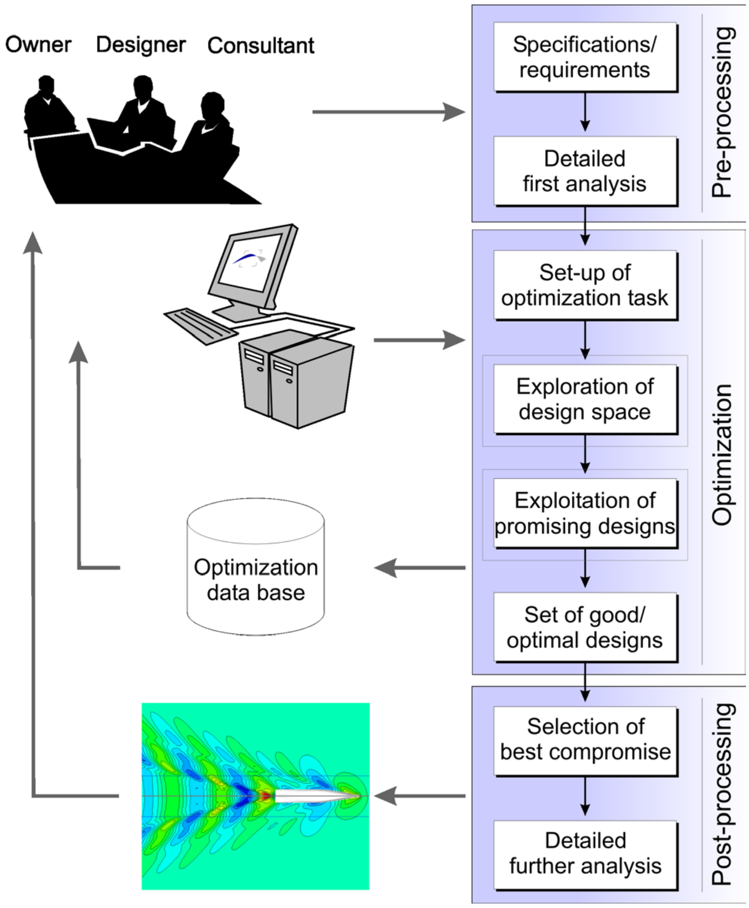


Figure 13 Automated optimization process including parametric hull form generation and numerical resistance computation

8 Objectives

While this setup can efficiently come up with a superior candidate it must be kept in mind that the selection of the objective function is crucial to the outcome of the optimization. Thinking of a racing yacht one generally thinks of speed to be the ultimate performance measure. However, modern racing yacht handicapping systems also use a simplified speed prediction of the boat. Therefore it is not necessarily the fastest boat that wins the race but rather a boat which prediction is less than its actual performance. Therefore the difference between these two numbers is in fact the ultimate objective (for a boat racing under these rules.) Figure 14 shows the results of a simplified optimization starting from an 10m IMS cruiser racer a), where b) depicts the lines of the hull optimized with respect to resistance reduction by means of a nonlinear Rankine source panel method, d) is using a regression formula based on an experimental systematic hull series and c) is trying to maximize the difference between these two methods by using the fraction of b) and d) as objective function. It is obvious that the outcome very much depends on how you formulate the objective function and also that the optimum race boat c) looks very different from the one using a first principle method b).
It must be noted that for this exemplary study only length and displacement were kept constant, however, for real world optimizations additional constrains such as hydrostatic stability may need to be included in the optimization process. Also for more advanced yacht optimization more than one objective must be taken into account, i.e. downwind speed and upwind speed.

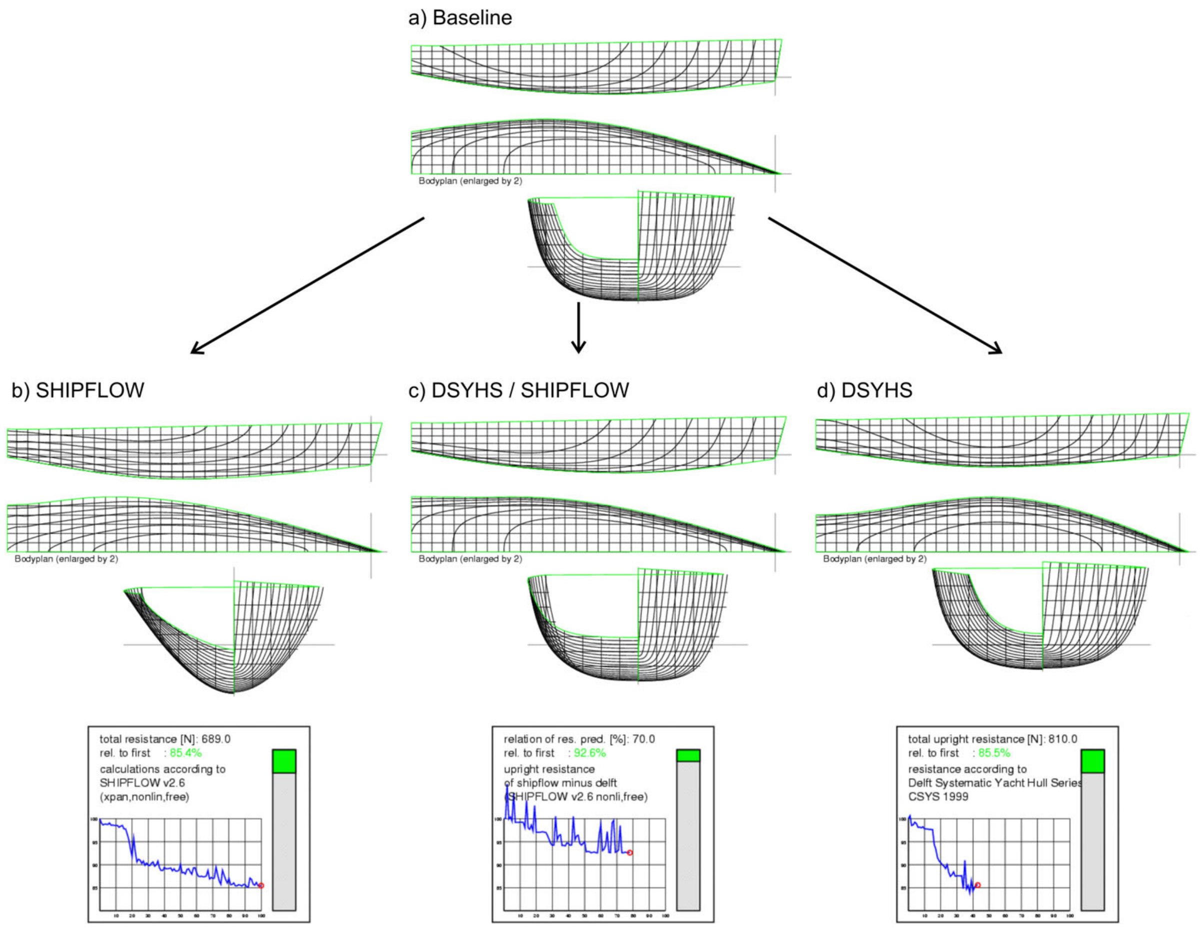


Figure 14 Downwind optimization of a 10m IMS cruiser racer using different objective functions. The graphs below show the optimization history for each setup. Resistance reductions of up to 15% could be achieved.

9 Summary

A brief overview of current methods on performance prediction of sailing yacht hulls has been given and a new approach for automated optimization is introduced. This approach is used successfully by FRIENDSHIP SYSTEMS on a daily basis for commercial ships and yachts as consultancy service for clients worldwide.

For sailing yachts the coupling of aerodynamic and hydrodynamic forces is crucial, however, complete handling of the aero- and hydrodynamic part by codes such as RANSE seems currently economically prohibitive although this might become a workable option in the future. Today, regression models from systematic numerical or model scale experiments build the basis for performance prediction, however advanced techniques such as the Real-Time Velocity Prediction implementation in the Twisted Flow Wind Tunnel can reduce the need for regression and provide results at a very fast response time.

10 References

[1] Max Oertz, Über Segelyachten und ihre moderne Ausführung, STG 1901

[2] Richardt, T.; Harries, S.; Hochkirch, K.: Maneuvering Simulations for Ships and Sailing Yachts using FRIENDSHIP-Equilibrium as an Open Modular Workbench, 5th International EuroConference on Computer Applications and Information Technology in the Maritime Industries (COMPIT 2005), Hamburg, May 2005

[3] Krebber, B. and Hochkirch, K.: *Numerical Investigation on the Effects of Trim for a Yacht Rig,* 2nd High Performance Yacht Design Conference, Auckland, February 2006

[4] Azcueta, R.*: RANSE simulations for sailing yachts including dynamic sinkage & trim and unsteady motions in waves,* 1st High Performance Yacht Design Conference, Auckland 2002

[5] Heppel, P.: *Accuracy in sail simulation: Growing fast sails*, 1st High Performance Yacht Design Conference, Auckland 2002

[6] Graf, K. and Renzsch, H.: *RANSE investigations of downwind sails and integration into sailing yacht design processes*, 2nd High Performance Yacht Design Conference, Auckland 2006

[7] Hansen, H., Jackson, P.S. and Hochkirch, K. (2003). *Real-Time Velocity Prediction Program for Wind Tunnel Testing of Sailing Yachts*. In *The Modern Yacht Conference*. RINA, Southampton.

[8] Harries, S.; Abt, C.; Hochkirch, K.: *Hydrodynamic modeling of sailing yachts*,
The 15th Chesapeake Sailing Yacht Symposium (CSYS), Symposium, Annapolis, 2001