THE ROYAL INSTITUTION OF NAVAL ARCHITECTS

6 DEGREE OF FREEDOM CFD APPLIED TO THE DESIGN OF HIGH PERFORMANCE RACING YACHTS

R Schutt, R Azcueta, and **N Rousselon,** Cape Horn Engineering, Spain

SUMMARY

This paper presents the application of multi-degree of freedom Computational Fluid Dynamics (CFD) simulations to high performance racing yacht design. It aims to demonstrate that simulations are a preferred alternative to tank testing when assessing overall boat performance. The methodology is based on experience gathered over the last 10 years of designing high end racing boats, especially in America's Cup and Volvo Ocean Race campaigns. As was done with auto racing and the automotive industry, CFD technology can be successfully transferred from race boats to general industry. In particular, when looking to maximize performance, yacht designers can now benefit from recent advances in CFD. Cape Horn Engineering is a company that specializes in hydrodynamic and aerodynamic CFD for the marine industry.
This paper presents a general yacht design philosophy based on simulations and specific applications of 6 degree of freedom (6-DoF) simulations in the design process.

1. INTRODUCTION

The effect of Reynolds-Averaged Navier-Stokes (RANS) free surface flow simulations on the design of high performance racing boats is undeniable. Especially in America's Cup and Volvo Ocean Race the application of these CFD techniques has led to unparalleled success.
The results achieved in these campaigns have made engineers and yacht designers, extremely confident that simulations, when applied diligently, can be a superior alternative to traditional tank and wind tunnel testing.
Simulations developed in the America's Cup environment require rigorous testing and validation to remain competitive at the highest level. The difference between two design candidates can be smaller than the experimental error when running the same towing tank test twice. Numerical simulations eliminate this inconsistency and offer fundamental advantages over physical testing.
Recently, industry leading design projects in which the authors were involved relied solely on CFD simulations. At Cape Horn Engineering we have forgone traditional towing tank and wind tunnel tests in favor of an exclusively CFD based design philosophy. Our simulations are cheaper, faster and more reliable than traditional tests. Simulations are run at full scale, which eliminates the inherent error of scaled test results. Enhanced flow visualization and force decomposition give designers a much greater understanding of flow phenomena. This relatively new technology can now be successfully taken from the racing environment and used for high performance projects in the marine industry in general.
In addition to maximizing velocity performance, CFD simulations can successfully be used to assess power requirements of motor yachts, balance of sailing yachts, the behavior and structural loads in waves, and windage and water on deck.
In this paper we will describe the underlying numerical methods first, then explain the general CFD based design philosophy for high performance sailing yachts, and finally show the use of new 6-DoF simulations in the design process.

2. NUMERICAL METHOD

For our simulations we use commercial RANS codes from CD-adapco; Comet and Star-Ccm+.
We have used Comet for more that 10 years with great success, applications and validation are presented in several papers, see [1-4] for details.
Focus is now mainly directed towards the use of Star-CCM+, which builds on Comet's strengths while developing a more robust, user friendly package that includes the latest physical models and solver technology (turbulence models, transition models, cavitation, integrated unstructured volume meshing polyhedral and trimmed cell approach, etc).
Both codes have shown to be very flexible and efficient to use thanks to user programming (Comet through Fortran or C user coding, and Star-CCM+ through a Java API).
Comet, when using its cell-based numerical capability, is still our tool of choice for highly accurate and fast free surface computations (where small design changes need to be evaluated). Star-CCM+ is better geared towards complex geometries and complex physics.
Numerical computations for marine applications involve the coupling of a RANS flow solver (with free surface capability) to a body motion solver and a mesh motion/deformation solver. The RANS equations are solved using a finite volume approach. Both solvers

handle any cell type and topology, including polyhedral elements.

Accurate viscous solutions require refined mesh resolution near the wall. Two turbulence models, k-epsilon and k-omega, along with wall functions, are generally used to decrease computational time, while keeping an adequate accuracy.

Second order accuracy in space (with face values and gradients) is achieved through the use of advanced interpolation techniques.

Free surface simulations have long been the strong point of Comet. Comet and Star-CCM+ both use a similar interface capturing approach; the free surface is modeled using a volume of fluid (VoF) method. The air-water interface is kept sharp using an high-order advection scheme based on the high resolution interface capturing (HRIC) interpolation scheme, see [5] for more details.

For fluid body interaction problems, the equations of motion are solved using a body motion solver. Body orientations and dynamics resulting from the forces acting on the body (viscous and pressure forces) are determined by integrating the equations of linear and angular momentum. External forces and moments (i.e. propulsion from sails or propellers) are added during this step. Basic simulations are free to sink and trim (2-DoF), while more advanced (seakeeping or maneuvering) can be completely free (6-DoF with moving control surfaces).

In cases where dynamic results are not needed (i.e. steady state simulations in calm water), several techniques are used to decrease total computational time. Whether in calm water or in waves, we preferably use a single moving mesh strategy when solving for single body motion. The mesh is not deformed but moved. This is a robust (large motion does not degrade mesh quality) and fast method (no deformation overhead) to handle the motion of the boat.

All of our simulations are processed in parallel on 4 to 16 cores; with 556 processing cores in our cluster we can run more than one hundred simulations per day.

3. CFD BASED DESIGN

Cape Horn Engineering has been involved in Volvo Ocean Race and America's Cup design campaings in association with Juan Yacht Design since 2003. During the first campaigns, ABN Amro and BMW Oracle Racing, a thorough validation with tank testing was conducted. In the most recent campaigns, Ericsson Racing Team for the Volvo and Team Origin for the America's Cup, the entire design is based on CFD simulations.

The following is a description of our design philosophy for the well funded Ericsson Racing Team campaign.

All hydrodynamic and aerodynamic simulations are run separately. Hydrodynamic simulations are used to research hull form, yacht behavior in waves, and appendage shape and position. Early in the design process, aerodynamic simulations are used to determine the sail forces, which are in turn used as input for the hydrodynamic simulations. Later we return to aerodynamic simulations in order to optimize sail shapes and investigate new sail concepts.

Our hydrodynamic cases are run using full size hull models with rudders, keels and foils. In aerodynamic simulations we model all geometry above the static water plane, including the sails, mast, boom, deck and hull. The rig is tilted to the correct attitude, accurately modeling heel, pitch and yaw. A varying wind profile is used to account for the boundary layer along the surface of the water.

For sail analysis we use parametric modeling and fluid structure interaction (FSI) codes. In parametric models we use CFD to find the optimal aerodynamic sail shape. Sail designers then develop a sail with the appropriate structural elements in order to achieve this optimal 'flying' shape. Parametric variation is done either by using a predefined matrix of variations, or by incorporating an optimizing algorithm in an iterative loop. In FSI models, the CFD code passes pressure forces into a finite element model which then calculates the deformed shape of the sail. The new deformed shape is trimmed by the sail designer and put back into the CFD simulation. This cycle is repeated four to five times until convergence is reached.

In hull shape studies we use fully appended models with a reference set of rudders, keels and foils. For appendage studies we use a set of reference hulls and change appendage concepts, shapes, positions and orientations. Each variation is evaluated by comparing the resulting forces (drag, side force, roll and yaw moments) and by comparing the flow characteristics using stream lines and other visual techniques.

The Volvo 70 Class boats present a new, very complex, design problem. Compared to previous America's Cup Yachts there are many more design variables; the Volvo 70's are designed to a box rule and experience sailing conditions from all over the world. Boat speed ranges from 6 knots as a displacement hull to 30 knots planing and surfing down waves. The boats also have canting keels and water ballast which drastically changes the displacement of the boat and the center of gravity. All of these variables lead to very large testing matrices. Here CFD becomes very attractive; each variable usually can be changed simply by changing a number and running the simulation again.

Our hull shape research program is quite extensive. The design spiral begins with the required transverse stability and waterline beam. We then obtain accurate sail force coefficients using our own aerodynamic simulations. Different sail sets are tested for upwind and downwind sailing in light and heavy air conditions. This is important, especially for very beamy boats, because the sail forces can have a large effect on longitudinal trim which changes the drag.

The hull shape investigation continues with studies of volume distribution, prismatic coefficient, transom width and immersion, bow fullness, etc. Hull shapes are organized with parent hull shapes and their derivatives.

This allows for easy analysis of trends and performance drivers and the final selection of a hull shape. After the final hull has been chosen and the lines have been sent to the builder, research continues with appendages and sails. We investigate the size, shape, and position of the keel, bulb, rudders and dagger boards. We adjust the transverse inclination, longitudinal inclination (sweep), alignment of the keel cant axis (if allowed by the class), pitch of the bulb, angle of attack of the dagger boards, etc. Different solutions and details for the attachment of foils to the hull are investigated.

Candidate boats are then run through race simulations to determine which design is the best. A Velocity Prediction Program, or VPP, is used to analyze trade-offs, such as stability versus drag, and to determine optimum balance. A Router program simulates the best course for each hull using statistical weather data for relevant parts of the world, and then compares the time needed to complete the course for each hull. Thus, the overall winner of the race is found in probabilistic terms. Other design variations, such as the position of a dagger board, are more straightforward to analyze and usually it suffices to compare the amount of drag at a given side force to draw conclusions.

In many cases sail and appendage design and modification is given a reality check when tested on the trial boat in real sailing conditions. During this on-the-water training period we are given valuable feedback from the real world that keeps us motivated and focused.

Finally, a set of seakeeping simulations are performed to investigate the dynamic behavior of the final candidate hulls. These simulations verify that what is good in calm water does not become detrimental in waves. Unlike a towing tank, no other simplifications are necessary; in our simulations, any wave direction is allowed, the boat is at full scale, the center of mass is in the right position and the moments of inertia will be the actual estimated values.

4. 6-DoF PERFORMANCE ANALYSIS

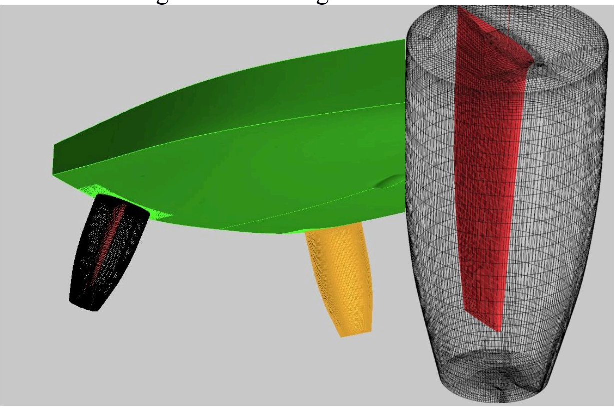
In traditional towing tank tests, boats are only free to move in heave and pitch. This results in test conditions that do not accurately represent real sailing conditions. With 6-DoF simulations, the boat is free to move as it would in the ocean, with all forces and moments balanced. Boat designs can be very accurately compared by applying a driving force and letting the boats move naturally until they reach equilibrium at their final velocity and attitude. All effects of a design change are readily apparent, results do not need to be interpolated, which can hide secondary effects of the change.

4.1 RUDDER BALANCE

In 6DoF simulations a boat with an unbalanced yaw moment will spin in a circle. To address this problem a rotating rudder can be added to the simulation. By rotating the rudder, the hydrodynamic moment generated by the boat is varied to balance the aerodynamic moment from the sails.

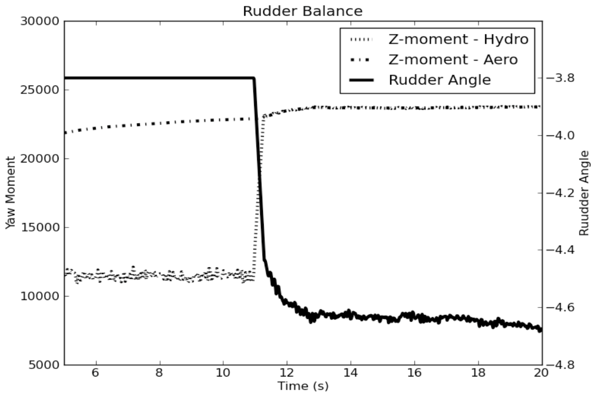
To integrate this rotating rudder a separate rotationally symmetric computational mesh is created around each rudder and a sliding interface is used between this mesh and the main hull mesh. Figure 1 shows the rudder mesh on 60ft offshore racing boat. The addition of this sliding interface adds 15% to the computation time, and is only used when needed.

Figure 1: Rotating Rudder Mesh



In wave cases a PID controller is used to rotate the rudder so that the boat maintains the proper heading. In calm cases, where the external forces on the boat are not varying, the controller can be set to balance the yaw moment directly and equilibrium is reached very quickly. Figure 2 shows the aero and hydro moments and rudder angle for the 60ft racer in calm water sailing. The rudder controller was turned on at 11s. The rudder angle quickly changes by 0.8 degrees and the hydro moment begins to balance the aero moments.

Figure 2: Moments with Balanced Rudder



Including the rotating rudder within the simulation itself, instead of calculating the needed rudder angle afterwards, allows the simulation to capture the additional effects that the new rudder angle has on the rest of the boat. For example in this case, the lift generated by the keel fin drops by 30% when the rudder angle changes and the overall boat speed increases by 0.4%. When multi-day ocean races are won by less than

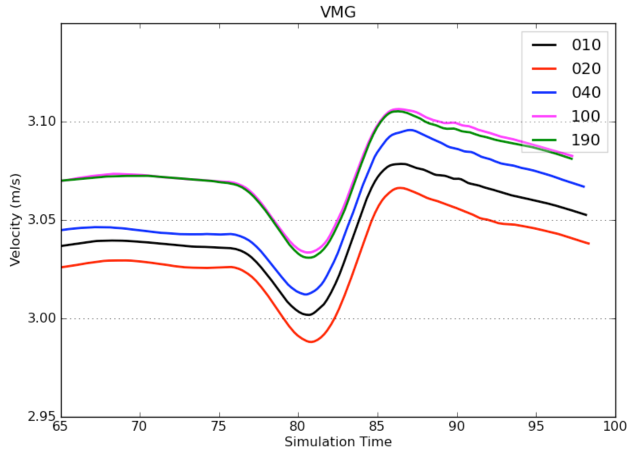
10 minutes, modeling this 0.4% of boat speed can be incredibly important. For this project, when the candidate boats where compared at this sailing point, the overall boat speed rankings switched when the rotating rudder was include, highlighting the importance of including a balanced rudder.

Currently this technique has only been used for rudders, but the same methodology can be used for any control surface. More advanced controllers can be tested and tuned for roll damping or lifting foil applications.

4.2 WIND GUST

With this 6-DoF capability in place a variety of dynamic boat behaviors can be modeled. Recently in the design of a TP52 racing yacht, the final set of hulls was put through a wind gust test. Each hull was allowed to reach a steady equilibrium and then subjected to a 10 second duration increase in wind strength. Figure 3 shows the velocity made good (VMG) response of the 5 different hulls over the course of the 10 second.

Figure 3: Wind Gust Response

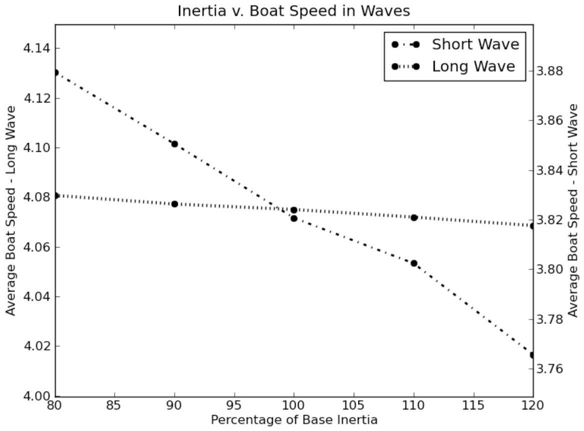


As the gust hits, each hull is initially pushed sideways and the VMG decreases, but after the gust peaks and begins to dissipate, the hulls begin to accelerate and are able to take advantage of the increased wind strength. Hull 040 was able to maintain a proportionately larger VMG increase for the longest period and gained the most ground during the gust. Without accurate 6-DoF simulations, assessing the performance of candidate designs in dynamic situations such as this wind gust would be very difficult and time intensive.

4.3 INERTIA VARIATIONS

A series of 6-DoF cases were used to assess the effect of varying the moment of inertia on performance in waves. Inertia values ranging from 80% to 120% of the base values were tested with two waves. A 39m wavelength 'long wave' was used in addition to a 14m 'short wave' . Figure 4 shows that as the inertia increases the short wave performance drops by 2.9% while the long wave performance only drops by 0.3%.

Figure 4: Boat Speed in Waves



Further analysis shows that the magnitude of the accelerations experienced in the short wave cases is double that of the long wave cases. As the inertia is 'eased the boat heels less per wave, but trims more. s increased trimming motion causes a greater drag on hull; however, with a greater heeling movement the l fin begins to drive the boat forward. This detailed part information can be very valuable when making ign trade off decisions.

APPLICATION TO A POWERBOAT

hull shape of this boat is relatively complex, uring spray rails and backward steps. Figure 5 shows ssure coefficient contours on the hull for a boat speed 9 knots, typical pressure peaks are visible.

speed ranges from low speed in displacement mode high speeds in planing conditions. The dynamic age and trim of the hull, which is of paramount importance in the higher speed range, is accurately captured by the simulations.

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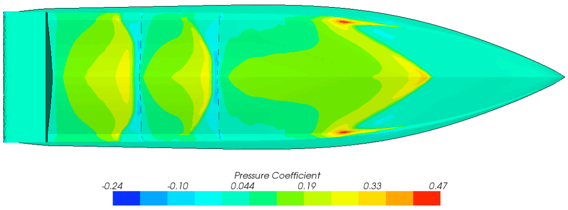


igure 5: Cp contours on hull at 29knots.

Seakeeping simulations were also conducted, with special attention to added drag, slamming, spray and water-on-deck, see Figure 6. Boat motion for a range of wavelengths and directions was evaluated by freeing between two and six degrees of freedom.

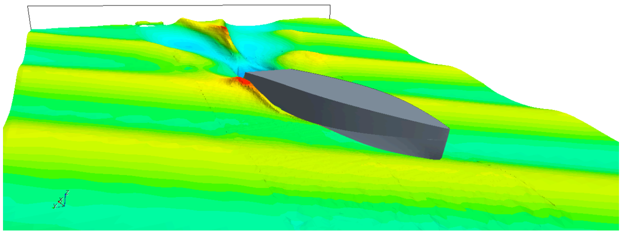


Figure 6: Seakeeping simulation.

4.5 APPLICATION TO A HIGH PERFORMANCE SAILING YACHT

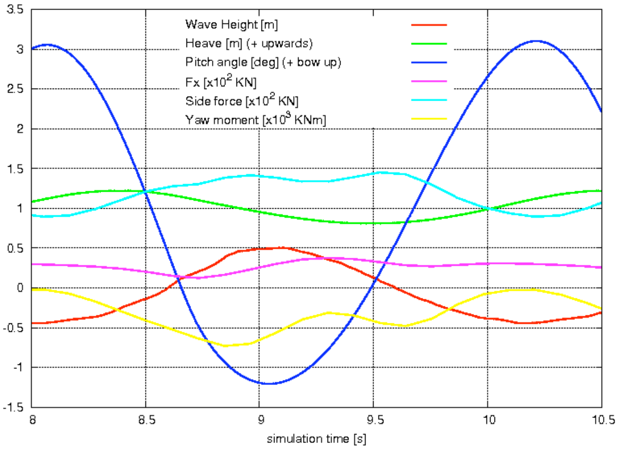
'Speedboat' is actually the name given to a high performance sailing yacht conceived to break speed records. She is a 100 foot canting keel yacht, with twin rudders and a very wide and powerful hull shape, see Figure 8.

Speedboat was launched in Auckland on 16 April 2008 and that same day underwent the structural test and sail trials, showing a perfectly balanced sail plan and appendages. This behavior would not have been possible without the use of well developed aero and hydro models using CFD, and a detailed VPP.

Today, Speedboat is probably the fastest mono hull sailing boat on the planet.

The simulations conducted for Speedboat aimed at producing a well balanced boat assessing the position of the sail plan and appendages. Furthermore, accurate performance data was obtained to be used as polars on board.

Figure 7: Yacht response in waves.



Simulations in waves were used to find the dynamic performance of the boat. Figure 7 shows typical results for such a simulation in waves. The wave height is 1 m and the wavelength 30 m at an incidence angle of 30 degrees from the bow. The yacht sails with a heel of 15 degrees at 16 knots. The diagram shows some of the output of the simulation for one wave encounter period.

To run these simulations an accurate and robust aerodynamic model was required. The model is based on the large library of sail-shapes that we have tested in the past.

In these simulations an early version of the rudder controller was used to find the final steady state condition. Figure 9 shows the motion history for a 6-DoF case: the boat is sailing with a true wind speed of 10 knots and a wind direction of 95 degrees. The rudder control system keeps the boat at a heading of 0.5 degrees.

Figure 8: 'Speedboat' reaching in her maiden outing.

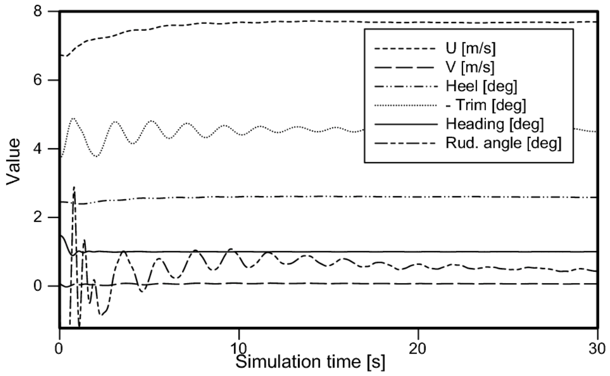


Figure 9: 6-DoF motion history.

5. CONCLUSIONS

In recent years, simulations using RANS codes have surpassed towing tank tests in accuracy, capability, and ease of use. This combined with detailed results and advanced flow visualization techniques gives designers a much greater insight into dynamics and flow characteristics. Using fully balanced 6-DoF simulations allows designers to get the most performance out of their boats.

We see these 6-DoF simulations being used to assess the balance of sailing yachts and the performance differences between design candidates. This methodology will eventually replace the classic VPP.

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7. AUTHORS BIOGRAPHY

Rodrigo Azcueta is the founder and manager of Cape Horn Engineering, specializing in marine CFD. He has a degree of 'Doktor Ingenieur' from the Technical University of Hamburg-Harburg, Germany. He has pioneered the application of RANS free-surface flows for ships and floating bodies.

Riley Schutt works as a project manager at Cape Horn Engineering, focusing on hydrodynamic development and multi-degree of freedom simulations. He has a degree in S.B. In Aerospace Engineering from the Massachusetts Institute of Technology in Cambridge, MA, USA.

Nicolas Rousselon works as a project manager at Cape Horn Engineering, with special focus on method development and aerodynamics. He holds a MSc degree in marine CFD from the University of Southampton, UK.