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THE EXTENSIVE USE OF A CFD TOOL IN THE YACHT DESIGN PROCESS TO ACCURATELY PREDICT HULL PERFORMANCE.

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Abstract. A CFD program is presented , which is used as a design tool for sailing yachts. The program can be used on a regular PC and with a small budget. The paper provides a description of this method, including the basic features and the mathematical formulation. Comparisons are made between the numerical predictions and tank testing data. The authors discuss the useful data obtained from the program, which helped the designers to improve the yacht design. The level of accuracy of this method is also discussed as well as the time and cost implications of using the CFD tool in the design process. The authors discuss the use of the CFD code in the design efforts for the Volvo Ocean Race yacht, Amer Sports one, and the IACC boat for the team Victory Challenge Sweden.

NOMENCLATURE

μ	doublet strength on a panel
σ	source strength on a panel
ρ	density of water
φ	total velocity potential
ζ	wave elevation
Φ	Basis flow potential
ϕ	perturbation potential
g	gravitational constant
n	normal vector
U	boat velocity
V	local fluid velocity

1. INTRODUCTION

This paper will discuss some recent applications of the computational fluid dynamics (CFD) program VSAERO/FSWAVE at Porto Ricerca Snc. (PRicerca) to the analysis of high performance sailboats for German Frers. Over the past 8 years PRicerca has used Analytical Methods, Inc. (AMI) software, and is the distributor of AMI software for Italy. AMI currently markets a series of commercial CFD packages ranging from 2-D airfoil analysis methods to 3-D Reynolds-averaged Navier-Stokes methods. One of these packages, VSAERO, is a widely used boundary element method (more commonly known as a panel method) that computes the steady potential flow past arbitrary configurations. Boundary layer routines are coupled with the panel method to provide the surface skin friction distribution and boundary layer displacement effects. FSWAVE is a module for VSAERO, which computes the non-linear characteristics of a free surface near an arbitrary configuration. VSAERO and its unsteady flow equivalent, USAERO, have been used extensively for marine applications, including the analysis of the wake wash generated by fast ferries (see Hughes [1],[2]), the analysis of both the steady and unsteady flow past propellers as well as propeller hull interactions [3], [4] and the prediction of submarine manoeuvring characteristics.

Some of the most recent projects for German Frers are the topic of this paper. PRicerca has been engaged to provide ongoing research to German Frers Jr. (Mani) on the design of boats for the Volvo Ocean Race and the America's Cup for the Victory Challenge Sweden as well as for German Frers' designs for production boats, high performance cruisers, and IMS yachts. The scope was to predict the performance characteristics of the hulls, keels, rudders and winglets in order to design the best package for these boats to fulfill the design targets.

The paper will first discuss the theory and implementation of the VSAERO/FSWAVE program. Then, results will be presented for a validation case study involving a yacht geometry. Finally the results of the CFD analysis for a simple yacht case will be presented along with some remarks concerning the time requirements and advantages of using these tools in the design process.

2. THEORY

2.1 General

VSAERO is a computer program for calculating the non-linear aerodynamic characteristics of arbitrary configurations in subsonic flow. Vorticity shed from the body at the trailing edge of a lifting surface or where flow separation occurs is assumed to be confined to a thin shed vortex wake sheet. Non-linear effects of the shape of these wakes are treated in an iterative wake

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relaxation procedure, while the effects of viscosity are treated in an iterative loop coupling potential flow and integral boundary layer calculations. A program module, FSWAVE, computes the non-linear characteristics of a free surface disturbed by an arbitrary hull configuration. This hull configuration can be either completely submerged of surface piercing. Multiple hull configurations can also be modelled.

VSAERO/FSWAVE uses desingularized source panels raised above free surface combined with normal VSAERO (source and dipole) panels on the ship hull surface to predict the steady flow past submerged or floating vehicles. The procedure for representing the free surface follows an approach similar to that developed by Jensen, Bertram and Söding [5]. Provisions are made for predicting the change in the draft and trim of a ship resulting from its forward speed, to model the flow past a ship travelling in shallow water, and to model the flow past lifting surfaces near a free surface. Hughes [6] provides a complete description of the program and the theory on which it is based, as well as a description of several validation cases.

The procedure can be use to predict the wave form produced and the wave resistance generated by a ship travelling through calm water with constant forward speed. The basic features of the module FSWAVE are:

- Source and dipole panels on ship surface.
- Desingularized source panels above free surface.
- Non-linear free surface boundary condition satisfied by iterative procedure.
- Ship equilibrium condition (dynamic sinkage and trim) satisfied during iterative process.
- Open and Radiation condition are fulfilled using staggered grids.
- Bottom effect in shallow water can be modelled by images.
- Fully separated transom sterns can be modelled.
- Lifting flows can be modelled.

2.2 Physical Problem

The basic problem to be treated consists of a ship moving with constant speed, *U*, in a channel of constant depth and width. Both the depth and width of the channel may be infinite and are assumed to be so in most cases. It is assumed that the effects of viscosity are largely confined to thin boundary layers on the moving wetted surfaces and that wake vorticity is essentially concentrated in thin vortex sheets and discrete vortices embedded in the fluid. Away from the boundaries the flow is assumed to be inviscid, irrotational and incompressible, and is therefore governed by Laplace's equation. The problem is equivalent to a ship being fixed in an inflow of constant velocity. The following boundary conditions must be enforced on the boundaries of the modelled fluid domain:

- Kinematic condition on ship hull: Water does not penetrate the ship's surface.
- Transom stern condition: For ships with a transom stern, we assume that the flow separates and the transom stern is dry. Atmospheric pressure is then enforced at the edge of the transom stern.
- Kinematic condition on the free surface: Water does not penetrate the water surface.
- Dynamic condition on the free surface: The pressure is equal to atmospheric pressure everywhere on the water surface.
- Radiation condition: Waves created by the ship do not propagate ahead.
- Decay condition: Far away from the ship, the flow is undisturbed.
- Open-boundary condition: Waves generated by the ship pass unreflected through any artificial boundary of the computational domain.
- Equilibrium: The ship is in equilibrium, i.e. trim and sinkage are changed such that the dynamic vertical force and the trim moment are counteracted.
- Bottom condition (shallow-water case): No water flows through the sea bottom.
- Side-wall condition (channel case): No water flows through the side walls.

The decay condition replaces the bottom and side-wall conditions if no bottom or side-walls are present. The radiation condition is not valid for transcritical depth Froude numbers when the flow becomes unsteady and soliton waves are pulsed ahead of the ship.

2.3 Mathematical Formulation

A Cartesian coordinate system is used to formulate the equations with the *x* and *y* axes on the undisturbed free surface with *x* pointing downstream and *y* pointing towards starboard. The *z* axis points upwards. The flow is described by a velocity potential, φ, whose gradient is the velocity,

$$\nabla\varphi = -\vec{V} \quad (1)$$

The total potential is replaced by a perturbation potential,

$$\phi = \varphi - \phi_{ref} \quad (2)$$

where the reference potential, ϕ_{ref}, is the potential which represents a uniform inflow.

$$\phi_{ref} = -Ux \quad (3)$$

The perturbation potential must satisfy Laplace's equation in the fluid domain:

$$\nabla^2\phi = \phi_{xx} + \phi_{yy} + \phi_{zz} = 0 \qquad (4)$$

2.3.a Formulation on Ship Hull

Every potential flow must satisfy the integral equations obtained from the application of Green's theorem to Equation 4.

$$\phi(p) = \frac{1}{2\pi}\iint_{S_B}\left[\phi(q)\frac{\partial\left(1/r\right)}{\partial \vec{n}} - \left(1/r\right)\frac{\partial\phi(q)}{\partial \vec{n}}\right]dS_B + \frac{1}{2\pi}\iint_{S_W}\left[\Delta\phi(q)\frac{\partial\left(1/r\right)}{\partial \vec{n}}\right]dS_W + \Phi_{fs} \qquad (5)$$

where:

- S_B and S_W are the surfaces of the ship and any shed vortex wakes respectively,
- $\vec{n}$ is the unit normal to the body or wake surface,
- r is the distance between the point p and the point of integration q,
- $\Delta\phi$ is the jump in potential across the shed vortex wake surface,
- Φ_{fs} is the potential induced by the desingularized source distribution above the free surface.

In VSAERO/FSWAVE the ship hull must form a closed volume and the free water surface does not form one of the surfaces of integration in Equation (5). The desingularized source distribution above the free surface lies in the fluid domain external to the ship, although only the flow below the actual free surface has any meaning. The first term in the first integral in Eq. (5) is the contribution from a normal doublet distribution of strength, $\mu = \phi / 4\pi$, and the second term is from a source distribution on the ship hull surface, $\sigma = -\vec{n} \bullet \nabla\phi / 4\pi$. The value of the source distribution on the ship surface is known from the kinematic boundary condition on the hull.

$$4\pi\,\sigma = V_{NORM} + V_{BL} - \vec{U} \bullet \vec{n} \qquad (6)$$

where V_{NORM} is a prescribed non-zero normal velocity for modelling the effects of inflow or outflow through the ship surface, V_{BL} is the boundary layer displacement effect using the transpiration technique and $\vec{U} \bullet \vec{n}$ is the normal component of the incoming flow.

2.3.b Formulation on Free Surface

The boundary condition on the free surface is not satisfied using a Green's Theorem approach to obtain the potential on the free surface, but is formulated in terms of the velocity and derivatives of the velocity field at the collocation points lying on the free surface. The kinematic condition on the free surface gives the following condition on $z = \zeta$.

$$\nabla\phi \bullet \nabla\zeta = 0 \qquad (7)$$

where ζ is the wave elevation, which for simplification is expressed as $\zeta(x,y,z)$ with $\zeta_z = \partial\zeta/\partial z = 0$. The dynamic condition on the free surface (atmospheric pressure everywhere on the water surface) produces the following expression at $z = \zeta$.

$$\frac{1}{2}(\nabla\phi)^2 + gz = \frac{1}{2}U^2 \qquad (8)$$

Combining the expressions for the kinematic and dynamic boundary conditions produces a condition without the unknown wave elevation $z = \zeta$:

$$\frac{1}{2}\nabla\phi \bullet \nabla(\nabla\phi)^2 + g\phi_z = 0 \qquad (9)$$

This equation must still be fulfilled on the unknown free surface $z = \zeta$. The potential, ϕ, and the wave elevation ζ are approximated by Φ and $\bar{\zeta}$. Equation 9 is then linearized about the approximated potential, Φ. The linearized expression and Eqn. (7) for ζ are expanded in Taylor series about $\bar{\zeta}$, and the resulting expressions are combined to give the following linearized expression which can be applied at the approximate wave elevation $z = \bar{\zeta}$:

$$\begin{aligned} &2\left(\vec{a}\nabla\phi + \Phi_x\Phi_y\phi_{xy} + \Phi_x\Phi_z\phi_{xz} + \Phi_y\Phi_z\phi_{yz}\right) + \\ &\Phi_x^2\phi_{xx} + \Phi_y^2\phi_{yy} + \Phi_z^2\phi_{zz} + g\phi_z - B\nabla\Phi\nabla\phi \\ &= 2\vec{a}\nabla\Phi - B\left(\frac{1}{2}\left\{(\nabla\Phi)^2 + U^2\right\} - g\bar{\zeta}\right) + \left(2a_1 - B\Phi_x\right)U \end{aligned} \qquad (10)$$

where $\vec{a}$ represents the particle acceleration based on the approximate potential:

$$\vec{a} = \frac{1}{2}\nabla\left((\nabla\Phi)^2\right) \qquad (11)$$

and B is the following expression introduced for simplification:

$$B = \frac{\left[\frac{1}{2}\nabla\Phi\nabla(\nabla\Phi)^2 + g\Phi_z\right]}{g + \nabla\Phi \bullet \nabla\Phi_z} \quad (12)$$

A complete derivation of Equation (10) is provided in [6] and [8]. Once a solution is obtained, a new approximation for the wave elevation can be determined from Bernoulli's equation:

$$z = \frac{1}{2g}\left(U^2 - (\nabla\phi)^2\right) \quad (13)$$

The nondimensionalized error on the updated free surface is then expressed as:

$$\varepsilon = \max\left(\left|\frac{1}{2}\nabla\phi \bullet \nabla(\nabla\phi)^2 + g\phi_z\right|\right) \Big/ (gU) \quad (14)$$

where "max" represents the maximum value from all the control points on the free surface.

2.4 Implementation

The problem is solved using boundary elements (source and dipole panels on the ship hull and desingularized source panels above the free surface). The desingularized source panels lie in a plane approximately one panel length above the still water surface. The position of the collocation points on the actual free surface are adjusted each iteration, but the desingularized panels do not move during the iterative process. In VSAERO, the condition of no flow through the hull (and side walls if present) is satisfied automatically using the boundary integral formulation approach to a panel method based on Green's Theorem (see [7]). In FSWAVE, however, the free surface does not form one of the boundaries of the integral equations, but rather the velocity and its derivatives are computed at the control points on the free surface and the appropriate boundary condition is satisfied directly at these points. VSAERO/FSWAVE can be thought of as a combined Green's Theorem/Velocity method approach to a panel method, where Green's Theorem is applied to solid bodies (i.e. the ship and side walls) and a velocity method is used on the free surface. This combined method requires that the ship hull configurations form a set of closed bodies. Two special problems are encountered which require that an iterative solution approach be used: (1) A nonlinear boundary condition appears on the free surface, and (2) The boundaries of water (waves) and ship (trim and sinkage) are not known a priori. The iteration starts with approximating

- the unknown wave elevation by a flat surface,
- the unknown potential by the potential of the free stream flow,
- the unknown position of the ship by the position of the ship at rest.

During each iteration, the wave elevation, the potential and the position of the ship are updated to yield successively better approximations to the solution to the non-linear problem as shown in Figure 1. Equation (14) is used to determine if the iterative process has converged. In general a converged solution is achieved in three or four iterations.

At the end of each iteration the velocity and pressure distributions on the ship hull are determined from the computed potential distribution on the hull. The pressure distribution is then integrated to obtain the forces and moments acting on the hull. A special procedure is used when integrating the pressure distribution on a surface piercing body to insure that forces on only the wetted portion of the hull are computed. The vertical force and the pitching moment are used to adjust the draft and trim angle of the ship before the start of the next iteration. If the ship has a transom stern below the still waterline, this is modelled by specifying V_{NORM} from Eq. (6) on the transom stern panels such that there is a sufficient outflow through the transom to produce atmospheric pressure at the edge of the transom. Details of the procedure for computing the sinkage and trim and modeling the flow about a transom stern are given in Hughes and Bertram [8]. The radiation and open boundary conditions are fulfilled using "staggered grids." This technique adds an extra row of desingularized source panels at the downstream end of the computational domain and an extra row of collocation points at the upstream end as described in Bertram [9].

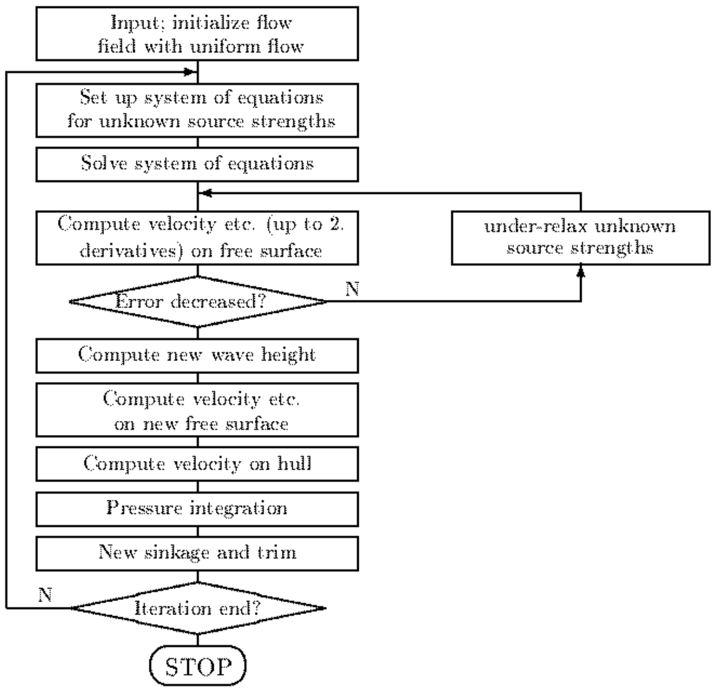

Figure 1. Flow chart of the iterative solution.

3. VALIDATION FOR YACHT GEOMETRIES

During the ongoing research process with German Frers, many tank tests have been carried out. Sometimes the data from these tests have been used to double check final solutions or different concepts and sometimes to validate our tools or to improve the way we use them. Thanks to this valuable information, we have been able to determine the reliability of the software, and have also learned the best procedure to follow when using the tools to obtain results which are even more accurate than tank test data. Using these tools we have been able to determine the influence on performance of very small changes to the geometry that even the tank tests were not able to see. Unfortunately much of this data cannot be presented in our paper because most of the data is subject to exclusivity agreements, but we have been authorised to present some data.

Figures 2 and 3 show a comparison between tank test results and VSAERO calculations for an America's Cup model geometry that includes a keel, rudder and bulb for a downwind condition and upwind condition respectively. As the figures show, the agreement between the VSAERO calculation and the tank test is very good. A clearer picture of the agreement is presented in Figures 4 and 5, which show the percentage difference between the VSAERO calculations and the tank test results. Unfortunately we were not allowed to show the actual numerical values of drag and speed so both the drag and speed scales have been scaled arbitrarily and do not represent real values. The tests have been carried out for the real conditions of an America's Cup boat.

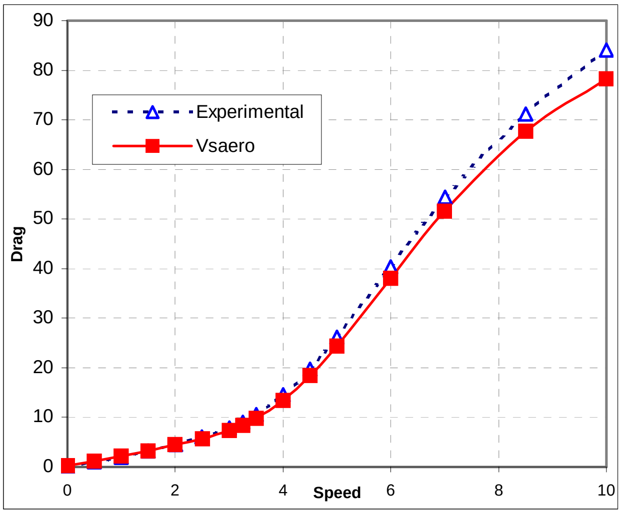

Figure 2. Drag vs. Speed for an America's cup Yacht in the downwind condition.

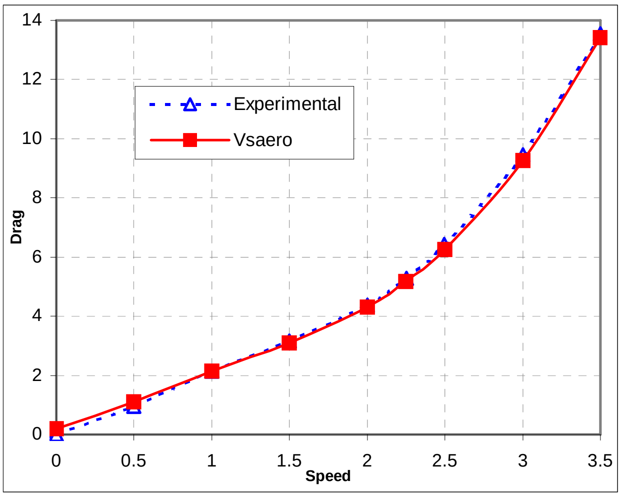

Figure 3. Drag vs. Speed for an America's Cup yacht in an upwind condition

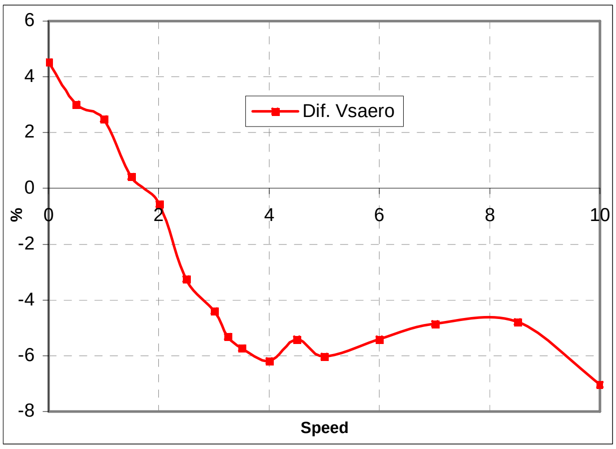

Figure 4. % error in drag vs. speed for the downwind case

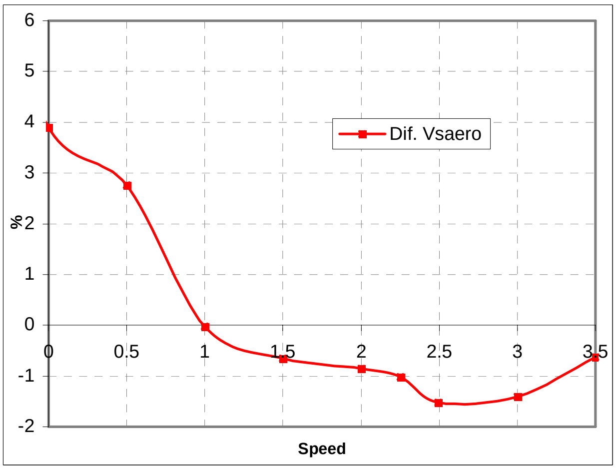

Figure 5. % error in drag vs. speed for the upwind case

The close agreement between drag values from the model tests and those calculated with our CFD methods is very encouraging because it shows that the tool is able to predict the total drag accurately. Drag is the most difficult force to predict accurately. The pressure distribution on a yacht hull is such that there is positive pressure in the bow and stern regions, and the pressure drag results from the difference between the large positive force resulting from the pressure near the stern subtracted from the large negative force resulting from the pressure near the bow. The drag itself is typically much smaller than the force operating on the bow or stern alone, and therefore small errors in the predicted pressures near the bow or stern or small errors in the predicted waterline shape near the stern could lead to a large error in the predicted drag. VSAERO/FSWAVE also predicts the side forces, lift, moments, the dynamic trim and draft of the boat, as well as other data, but these other forces are much less sensitive to small errors in the predicted pressure or wetted length, and are easier to predict accurately.

America's Cup boats are especially challenging for CFD programs. The dynamic waterline length is very different from the static waterline length and changes with speed. Small errors in dynamic waterline length predictions lead to large errors in the predicted drag. Also, the yachts have keels and rudders which generate lift and shed vorticity, which results in induced drag as well as additional wave making drag, so the software must be able to see the correct pressures and forces on these lifting surfaces. Some programs cannot accurately predict the total drag, but are still able to predict the performance difference between two different geometries. However, if the program is unable to predict the correct total drag, there are certainly some details missing in the calculations which would make it impossible to completely optimise the yacht.

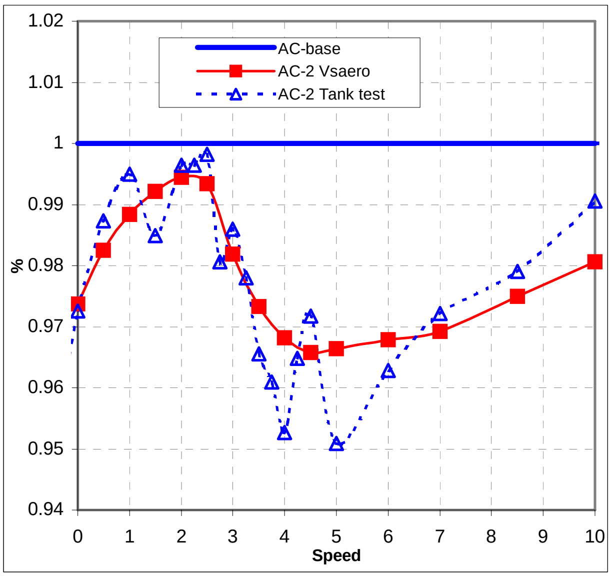

Figure 6 Percentage difference in drag on two different Americas Cup yachts calculated with VSAERO and tested in a towing tank.

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4. DATA COLECTED IN THE CFD ANALYSIS

To describe how we used the CFD tools to help design better yachts, we will present some of the data collected on a cruising yacht (Ticketitan) designed by German Frers. Figure 7 shows the geometry of the yacht.

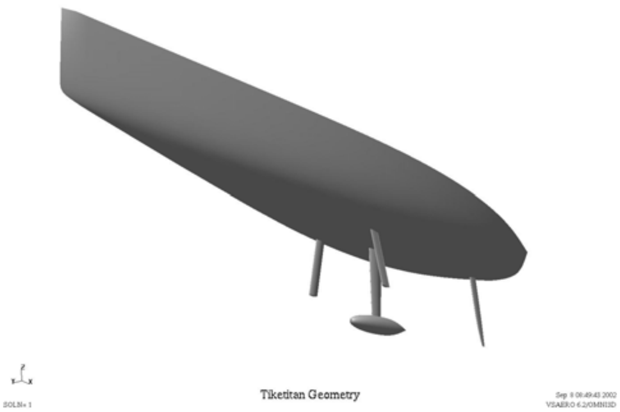

Figure 7. Cruising yacht designed by German Frers.

We can first look at the total drag and also determine the various contributions to the drag: frictional drag, wave making drag, and induced drag from the lifting surfaces. The side force is predicted as well as the longitudinal location at which the side force acts. (see Table 1). This information allows us to check the mast and sail positions and to evaluate the keel and rudder areas and positions to make sure they are correct.

Speed (Knt)	Side Force (Kg)	Total Drag (Kg)	Frictional Drag (Kg)	Presure Drag (Kg)	Longitudinal center of pressure (%)
11.00	3423	646	371	274	0.55

Table 1. General results for cruising yacht 92` L.O.A. High Performance Cruiser with yaw and rudder angle.

Then we can isolate the drag and the side force contributions from the different components (hull, keel, rudder, bulb, see Table 2). By doing this we will check if some component is contributing too much or too little to the drag or side force.

	Dagger board	Keel	Bulb	Rudder
Total Drag (Kg)	39.6	32.8	34.7	72.1
Side Force (Kg)	1766.4	215.9	20.0	1105.4

Table 2. Drag and side force on the appendages for cruising yacht with yaw and rudder angle.

Then we can look at the dynamic pressures plots on the surface of the entire geometry to understand where the significant contributions to the drag and lift are located. We can also look at the streamlines and examine the boundary layer thickness and skin friction drag distributions.

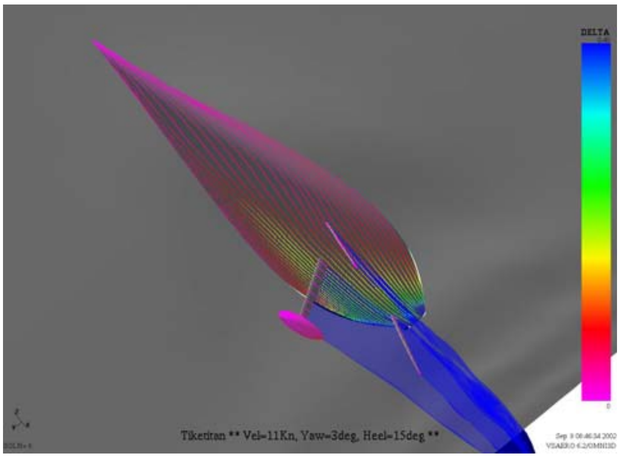

Figure 8. On-body streamlines with boundary layer thickness and wake visualisation.

If necessary we can even visualise the flow external to the hull, and examine the off-body pressures or upwash or downwash flow angles in the vicinity of an appendage. This helps us to understand the interaction of a wing or rudder with the local flow, which is disturbed by the hull and other appendages. This in turn helps us determine the best location to place a winglet or rudder.

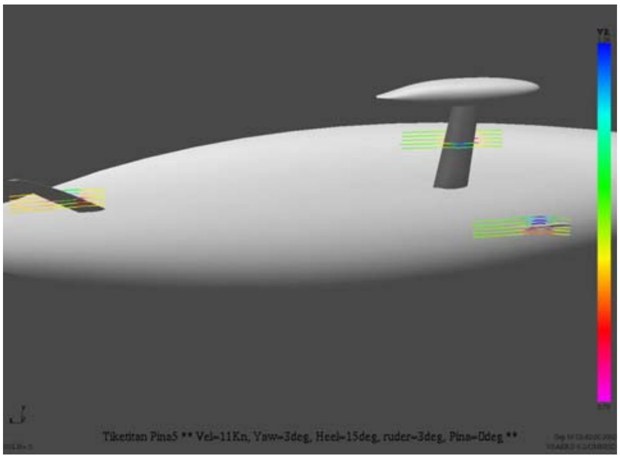

Figure 9. Off-body streamlines on the rudder, dagger board and Keel, with off-body velocity visualisation.

The analysis should be made for the sailing condition at which we would like to improve the performance of the boat. The CFD tool is like having our personal tank testing facilities in our office, as we are able to predict the performance with just a mathematical description of body surfaces. If we are not happy with the performance of a geometry, we can examine the details of the flow and produce a modified, improved geometry with a better understanding of the characteristics of the flow past the previous geometry. This process is generally repeated many times in order to improve our model as much as possible before producing the final geometry.

5. CONCLUSIONS

The CFD analysis tool VSAERO/FSWAVE was used to analyse, design and optimise German Frers' race and cruising yacht boats. The results from the CFD analysis compared well with scaled tank tested models. Good agreement was obtained both in the prediction of the total forces and in predicting the difference in performance between design variations.

In June 2000 we began working on the design of a Volvo Ocean Race yacht just 15 month before the start of that race. For that effort we had to start more or less from scratch, as we had not previously designed a yacht for this type of race, and we did not have all the data that our competitors had available from their design efforts during the previous Whitbread race. We also started working on the design for the Swedish America's Cup team in November 2000 with a small budget for research. However we used our tools to complete an accurate research program and fulfilled the design target efficiently and in time for the boat construction. VSAERO/FSWAVE proved to be a key for the success of these two design efforts.

One of the difficulties in using extensive model tests to improve the performance of a design are the long times required for model construction, testing and processing of the data. Also, without a large research budget, the cost of extensive tank testing makes it an option not suitable for small projects.

We believe that the use of CFD in the design process is also essential in helping to understand the results that come from tank testing. Today CFD is very reliable and in the future it will be used more often even on small projects, and the amount of tank testing required will most probably decrease.

During this 2003 America's Cup many teams have spent a lot of money on research with a large staff working in their design offices. In addition many teams had budgets sufficiently large to change parts of their boats several times and to test improvements full scale in real conditions. Many teams also had the benefit of data and experience from previous America's Cup campaigns. We are a very compact design team that communicates and discusses the design with each other using our time and resources in a very efficient way. So far, we believe our work has been very successful. Our design finished 3^{sd} in the Volvo Ocean Race, and we will have to wait and see what will happen during the America's Cup.

Acknowledgements

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