APPLICATION OF RANS CFD CALCULATIONS TO THE DESIGN OF SAILBOAT HULLS

Philippe Pallu de la Barrière, Jérôme Védrenne
Centre de Recherche pour l’Architecture et l’Industrie Nautiques (CRAIN)

Introduction

For many time, America’s Cup projects have put efforts to develop and to use CFD codes to perfect hull shape. Those codes are used to compare candidate design performance and to analyse flow around a hull in order to improve its shape. Tools that have been commonly used for fifteen years are potential flow code, with or without additional boundary layer calculation, which do not take properly into account non-linear and viscous flow effects where tank testing gives more precise global results but few indications about flow properties. The “box” rules of IACC, the experience from previous editions and the high level of the competition lead to look for small differences between hull shape inducing small, but sensitive, drag differences. For the America’s Cup 2003 campaign, RANS (Reynolds Averaged Navier-Stokes) codes with free surface were for the first time available with reasonably good computational time and practical efficiency. The authors were involved in the design team of the French challenge for the America’s Cup and have put efforts to find useful applications of the RANS code ICARE for studies of hull shape performance. ICARE code is a RANS solver, developed at Ecole Centrale de Nantes, for calculation of three-dimensional, turbulent, incompressible, unsteady, free surface flow around a hull. It has been used to evaluate and to compare canoe body only performance in steady state, with free trim and sink and to explain some drag differences by the local behaviour of flow like vorticity, helicity or dynamic length. Then, we will describe the method used to practically get consistent results on a large number of hulls, discussing mesh size, accuracy and computational time. Then we will show, using example of IACC and Open 60’ hulls tested in tank test, how can RANS CFD improve results compared to those delivered by potential flow calculation. We will also show for those precise cases how analysis of local parameters can provide a guideline to improve performance of the hull shape.

1. Achievement and limitations of the potential flow calculation for hull and appendages of sailing boats.

1.1. The REVA code

REVA code is a potential flow program with linear free surface condition, developed by G. Delhommeau and J-J. Maisonneuve from Hydrodynamic Naval Laboratory (LHN) of Ecole Centrale de Nantes (ECN). Based on Rankin singularities, full method is described in [4].

Since 1992, ECN and CRAIN have carried out a collaborative work in order to evaluate and to develop REVA applications to hydrodynamic calculation of sailboat. Trough various projects such as IACC, Multihull OPEN 60’ or The Race, IMS 50’, Monohull OPEN 60’ for which experimental data and sailing feedback are available, the authors have tried to delimit and to extend, when it was possible, the field of application.

After having optimised parameters in order to have no sensitivity to the mesh size and reduced CPU time, then having connected dedicated meshing program MACAO, developed by B. Alessandrini, with CAD, the use of REVA became light and even interactive, with a CPU time for a calculation on a modern PC not exceeding 15’ for canoe body only and 40’ for a hull with appendages (free heave and trim).

1.2. Application to calculation of the wave resistance of sailboat hull.

REVA is a useful tool for evaluation of the influence on resistance of main parameters such as water line length or beam LWL and BWL, displacement Δ, prismatic coefficient Cp or location of buoyancy centre LCB.

According to our experience, REVA can be applied to the study of smooth hull at least with the same level of confidence than well know

regression formulas from J.Gerritsma, J.A.Keuning and A.Verluis ([5]). Resistances from REVA are rather shifted down comparing tank test results (Figure 3) while the field of application of REVA for comparison purpose is more extensive than using regression formula's.
Other interesting effects are rather well provided by REVA like dynamic heave and trim, upright or heeled.

The main limitations of REVA are inherent to the linearity of the free surface condition and to the non-viscous potential flow assumption. Since linearity of the free surface condition prevents accurate study of overhangs, LHN has done a lot of work to implement a nonlinear free surface condition. Although good convergence and realistic figures of free surface were found, associated resistance calculation was very unstable and too much sensitive to the meshing. This way has finally been given up.
The non viscous potential flow assumption can lead to great inaccuracy for the drag generated at the stern of the boat by, for example, immersed transom or asymmetric water line when heeled. As a result, REVA is a limited, and possibly dangerous to use, help to design race boat stern that have to comply with rules taking into account aft girth length (IACC) or without limitation on transom immersion.

1.3 Application to the calculation of appendage resistance.

Calculation of appendage lift and associated drag are performed by using a fixed planar wake. As for free surface, many attempts have been done in order to relax the wake. This gave no improvement but a loss of stability of the calculations.
Comparing to tank test or wind tunnel test, lift slope is right where drag is underestimated. For example, winglet effect on induced drag is always optimistic although effect of incidence of winglet on induced drag is realistic.
Since REVA is more dedicated to free-surface effects, more interesting applications are the prediction of wave drag created by lift and interaction with hull especially when the boat is heeled.
For this purpose REVA predicts accurately the wave interaction drag between hull shape and longitudinal appendage location.

A first example of application is the tuning of an OPEN 60' appendage configuration ([7]). A classical configuration to create side force for this kind of boat is to associate a canting keel with twin asymmetric centreboards (see Figure1). The canting keel provides greater stability but because of its large effective heel and the vicinity of the water surface, its effective draft is low.
Leeward centreboard works vertically, as far as possible of water surface, and its asymmetry allows to control leeway angle. Used in 1999 for the design of SILL (skipper R.Jourdain, design M. Lombard), recognized as a very fast OPEN 60' of this generation, REVA allowed us to find asymmetry, span and location of centreboard as well as incidence angle of canting keel that we can get by inclining the axis of canting.
A good effective draft and a right balance of the boat have been provided this way, avoiding tank testing unfortunately too expensive for this kind of project.

A second interesting example is the work that we have carried out on effective span of foil of 60' trimaran. For several years, this kind of boat has been fitted with a straight laterally inclined foil located on leeward hull to create side force and vertical force, in order to lift and trim aft the leeward hull. REVA calculation of the hull fitted with foil has shown that important wave drag appears with lateral inclination, due to the vicinity of water surface, especially at the root of the foil (Figure 2). Moreover the resulting hydrodynamic force on foil is slightly more horizontal than the perpendicular to the span of foil. Hence, increasing vertical force by larger inclination cause a large amount of drag. Taking into account those results, and the fact that foil has to be removable while sailing, M. Lombard has designed a curved foil in order to be less close to the water surface. The first version, tested on 60' trimaran "Banque Populaire 2" has proved a great efficiency. Then, after complementary REVA analysis, we proposed to reduce again the radius of curvature. Trimarans first using those foils, such as "Fujicolor 4" or "Sergio Tacchini" noticed that they can use foil at lower boat speed (14 knots) than previously, for example upwind or downwind in medium breeze, when foil was used exclusively at higher speed (reaching or heavy breeze). Since foil became competitive earlier in speed, it proves that lift-drag ratio of foil had been improved. During 2003 circuit almost all 60' trimarans were fitted with curved foils.

1.4 Conclusions

Potential flow with linear free surface method remain a useful, easy to use, tool to study main hull parameters and appendages efficiency at the predesign state if only minor viscous effect are expected. However, this kind of tool cannot be longer used for high-level optimisation like for example IACC hulls.

2. RANS calculation of sailing boat hulls

1.1 The ICARE code.

Reynolds Averaged Navier Stokes (RANS) calculation is performed by several industrial codes for many years. RANS code dedicated to hydrodynamics has appeared as research code for only a few years. ICARE code belongs to this family. Since 1996, B. Alessandrini and G.Delhommeau (LHN-ECN) have continuously developed it, with financial support of the Defence Hydrodynamic Laboratory (DCE).

ICARE code provides calculation of three-dimensional, turbulent, incompressible, unsteady, free surface flow around a hull. More details about methods used in ICARE can be found in [1], [2], [3]. Last release of ICARE are able to compute flow around appended hull however, since we have no consistent result for that, we will only describe in this paper our experience of calculation on canoe body alone.

As for REVA code, the preliminary part of our work was to adjust meshing parameters with regard to robustness, insensitivity and minimal mesh size in order to limit the CPU time. The task here is to achieve a sufficient number of cells into the boundary layer avoiding exponential computing time. (Computing time ratio with ICARE is approximately proportional to twice the number of cells ratio).Fortunately, due to the relative smoothness of canoe body only, an amount of 8E4 cells is enough to perform accurate calculations. Increasing the number of cells don't change significantly the computed forces and do not change at all the gap between forces for different hulls. In comparison, appendages calculation that we have performed with the industrial code RADIOSS needed at least 1E6 cells to provide realistic lift on winglets. Moreover, we have used a time extrapolation formula based on Havelock estimation of wave drag time evolution of during acceleration in order to limit the number of iterations to 500. As a result, CPU time used on a modern PC for one attitude calculation with free heave and trim remains less than 90' that allows ICARE to be used without need of an expensive computer.

Regarding meshing process, the first step is to mesh the hull surface with a standard geometry (Figure 4). This has been achieved (almost) automatically using a homemade OLE macro in MSURF. Then 3D mesh is calculated at each time step by ICARE (Figure 5).

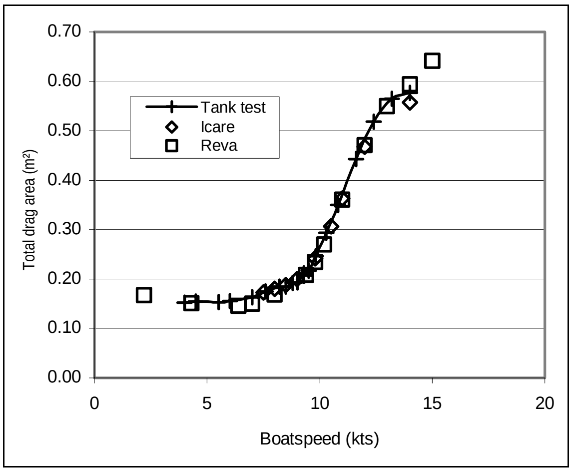

Figure 3 Measured and calculated upright total drag surface of an IACC hull.

1.2 Calculation of IACC hulls

Work of Yaka Design Team for the French Challenge of Le Defi 2003 was the first serious attempt to include ICARE calculations into a design process. Since available budget and time allowed us to tank test no more than ten original designs, it was for us an important challenge to have an efficient CFD tool, at least as a guide line and as an analysis mean for the hull design program.

From a purely economic point of view, global budget to compute twelve runs for fifty canoe bodies with ICARE was approximately the global cost of tank testing thirty runs for one canoe body only at a one to fourth scale.

However, taking into account the previous experience and mistakes that occurred using REVA with too much confidence, a great attention was given to validation of ICARE calculations and it has been agreed by Design Team that ICARE prediction would not be the only criteria to select hulls to be tank tested.

As shown in Figure 3, ICARE results for upright resistance are in quite close agreement with measured data. Although ICARE performs better than REVA for IACC upright resistance prediction, it is not the most interesting improvement that it provides. Since RANS calculations become really powerful when important turbulence and non-linear effect occurs, we will be more focused in this paper on the analysis of the flow past the stern of the hull.

Tank tests which are used here for comparison purpose, were carried out at DERA by Yaka Design Team during last Le Defi Challenge. CFD calculations have been carried out at CRAIN in the same context.

Let's keep in mind that IACC stern design is governed by IACC rules which estimate dynamic water line length LM by adding a static waterline length LBG measured at a height of 200mm above water plane plus a girth correction G that increases with forward or aft chain girth above a fixed maximum value.

Moreover, the longitudinal slope of hull near the aft end of flotation must be less than 12.5° and hollows on the hull are not allowed.

Hence, designers aim to get the maximum "effective" waterline length, avoiding G penalty nor having too much LBG, which would reduce quickly sail area.

Reducing hull slope at stern, in order to increase dynamic length, is obviously the first idea, that moves the centre of buoyancy forward and becomes rapidly a problem especially with narrow hull. Since the main interest with narrow hull is the possibility to increase dynamic waterline length when the boat heels, we can see that there is no obvious solution to maximize the dynamic waterline, but rather a fine design compromise to find, or, at contrary, a breakthrough based on lacuna in the rules wording.

An example is the HULA stern of the two last Team New Zealand boats that was the most dramatic attempt to use rules lacunas to increase dynamic length.

As we can see on the different designs shown in Figure 6, attempts to get longer heeled geometric waterline can produce sharper hull especially in transverse sections at stern. The first design CB1 is a fair rounded hull, in the spirit of TNZ32 (winner AC 1995) or ITA45 (winner LV 2000).

The second hull CB2 is a radical hard chine hull designed for FRA46 (6th Sens) for LV 2000.

It's obvious from those drawings that static waterline of CB2 at heel is slightly longer than CB1 one, due to the hull narrowness and to the hard chine that extend far in front in order to limit the move forward of the centre of buoyancy. However, heeled waterline (cutting hull surface by heeled planes) looks not so symmetric for CB2 than for CB1. Moreover, CB1 waterline curvature decreases slowly when going to the stern whereas on CB2, and especially on the windward side, curvature decreases quickly from a high value to zero.

Following a intuitive bi-dimensional analysis, we can expect that velocity of the flow to windward will be very slowed after the maximum of curvature, hence, when windward flow and leeward flow meets, they would develop a mixing layer creating a large vorticity in the wake of CB2.

Because this kind of effects are not taken into account by non-viscous code, REVA results for these two hulls (Figure 7 and Figure 8) favoured CB2. CB2 resistance decreases very quickly with heel, so the trade off between the loss of righting moment, due to narrowness, and the drag reduction is positive.

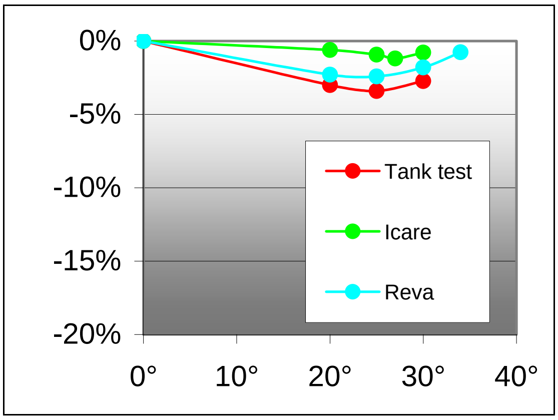

Figure 7 Tank testing data, ICARE and REVA calculation for CB1 when heeled

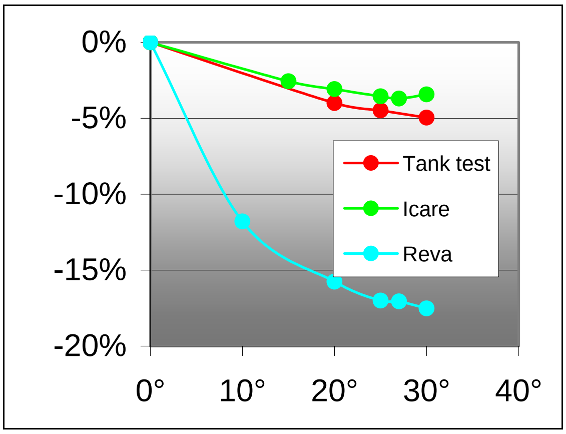

Figure 8 Tank testing data, ICARE and REVA calculation for CB2 when heeled

Tank test data of the two hulls shows that the reduction of resistance of CB2 due to heel is less than expected by REVA, although there is good correlation between CB1 calculation and test.

An analysis of tank test form factors, obtained by the Prohaska method, gives some information about the viscous drag of the designs. The form factors have been evaluated for three different heel angles and results are presented in Table 1. CB1 and CB3 have higher upright form factors than CB2 but which do not increase a lot with heel, whereas CB2 shows a very good form factor upright that increases a lot when heeling, so we can suspect here serious viscous problems.

Heel Angle	CB1	CB2	CB3
0°	1.07	1.04	1.09
15°	1.08	1.10	1.10
30°	1.10	1.12	1.10

Table 1 Tank test form factors for ACC hulls

Then, having a look on ICARE results, we can see that both CB1 and CB2 results on heeled resistance are well correlated with tank test results. This proves that taking into account vorticity and non-linear effects of free surface can upgrade the reliability of CFD results for the prediction of hull resistance.

ICARE provides also local variables as flow velocity and turbulent viscosity. Figure 9 and Figure 10 show streamlines near the aft part of hull of CB1 and CB2. Red points on curves represent fluid particle locations at successive time steps. More velocity shear appears for CB2 than for CB1.

Difference of turbulent viscosity level between the two hulls is not obvious whereas, as shown in Figure 11 and in Figure 12, helicity (defined as the scalar product of velocity by curl) is greater for CB2 than for CB1, and that, especially on the hard chine area where the maximum shear of velocity occurs.

Occurrence of vorticity in the flow means that flow kinetic energy has been created by hull motion. The amount of created kinetic energy in a volume of water of length L is equal to the work of a drag force for a motion of hull of length L. Created kinetic energy is progressively dissipated by viscosity and replaced by heating of water. Vorticity without helicity correspond to small structures, which dissipate quickly. It's typically the case of vorticity created in the turbulent boundary layer of the hull. Vorticity with helicity correspond to large vortices eddies which are persistent. It's typically the case of vorticity created by unstable wakes or mixing layer found behind lifting surface (keel) and hull stern. If we look sufficiently far behind the hull, we will see only vorticity presenting helicity because vorticity without helicity has been already dissipated.

Hence correlation between helicity and the wake energy (i.e.: form factor) is physically justifiable and, if we consider the example of CB1 and CB2, ICARE calculation of helicity seems helpful to control form factor.

In order to illustrate the capability of ICARE analysis, we present the analysis of the hull CB3 that was designed to obtain at the same time a reduced amount of helicity, a long heeled waterline and a high prismatic coefficient. Complying with those criteria has been achieved by designing hard chine at the stern with straight symmetrical heeled waterline, as shown in Figure 6. Therefore amount of helicity has been limited (Figure14) and heeled drag predicted by ICARE has been reduced, then those results were confirmed during tank tests (Figure 15).

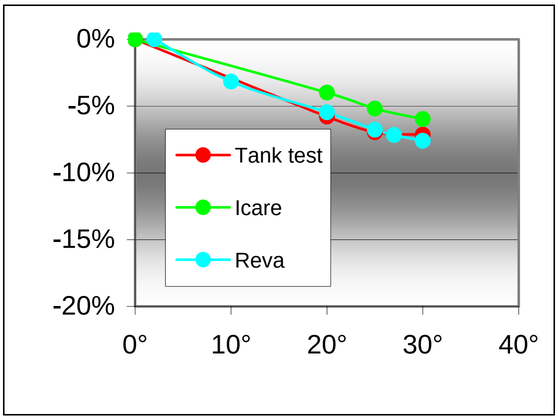

Figure 15 Tank testing data, ICARE and REVA calculation for CB3 when heeled

Moreover, if we come back to upright resistance, we can see in Figure 16, Figure 17, Figure 18, that ICARE prediction are slightly better than REVA especially regarding the evaluation of the "hump" in the resistance curve due to higher prismatic coefficient of CB2 and CB3

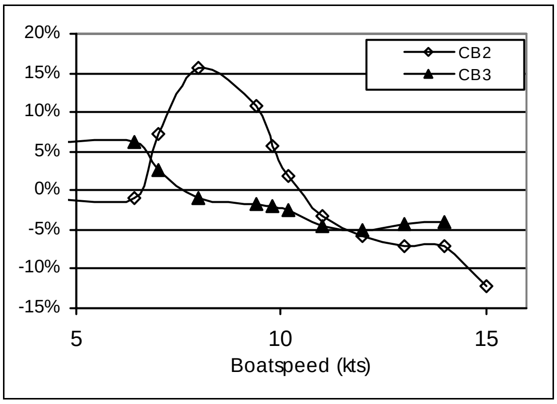

Figure 16 REVA prediction of upright resistance for CB2 and CB3 relatively to CB1

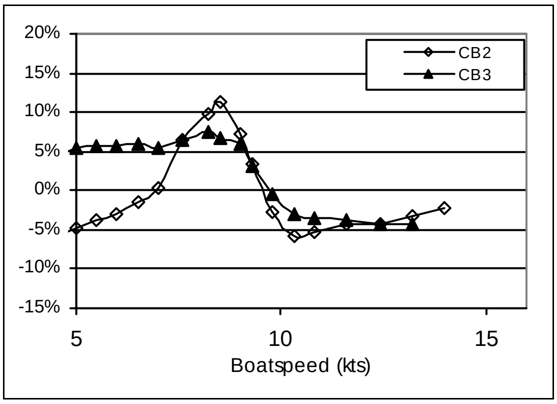

Figure 17 Tank testing measurement of upright resistance for CB2 and CB3 relatively to CB1

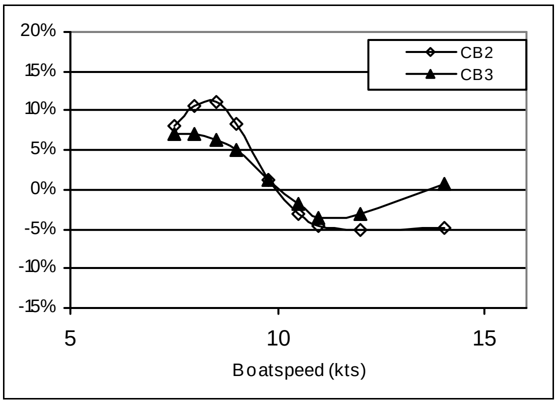

Figure 18 ICARE prediction of upright resistance for CB2 and CB3 relatively to CB1

1.3 Calculation of OPEN 60' monohull.

Length overall is the only hull dimension limited by the OPEN 60' rules. Oceanic races as Vendée Globe Challenge favoured light and wide hull in order to achieve high speed downwind and at reaching. On the other hand, despite a great righting moment, upwind performance are quite poor, less than expected from VPP calculations based on simplified hydrodynamic formulas or potential flow calculation as REVA, to estimate hull resistance. Of course, we could guess that this lack of performance stems from some underestimated drag, such as added resistance in wave, or windage due to the so beamy hull, or from a limited sail plan efficiency because of the undersized deck hardware, but all deductions lead to some hydrodynamics effects.

Unlike ACC hull, due to the rule, OPEN 60' hulls don't have overhang and transom is slightly immersed in static position. Moreover the wetted area quickly decreases with heel (Figure 19) and Froude number can be rather high since those boats can achieve speed up to 25 knots. Those characteristics don't favoured the use of linear potential flow method like REVA therefore we expected improvement by using ICARE for calculation of heeled drag.

Comparison between tank test, Reva and Icare results has been done on a Berret-Racoupeau design, which is the only one Open 60' hull we have tank test results for.

Those tank tests were carried out on a 1 to 7th scale model, at the University of Liège by Pr. Marchal, according to CRAIN specifications.

To achieve REVA drag calculations on this kind of hull, an assumption has to be made about the form factor value to compute the viscous drag. This can become tricky because of the unusual flat immersed body and because of the large waterline variation with heel

Upright resistance curves (Figure 20) show that REVA underestimates total drag up to 20%, where ICARE stays close to experimental data. Moreover, REVA calculation, with free trim and heave do not converge for boat speed over 15 knots (Fn=0.55) due to a great variation of the longitudinal trim moment. At a boat speed of 18 knots (Fn=0.7), the difference between Icare and experimental data is only 7%. Above this speed, results are less consistent but remain very good, compared to other evaluation means, with a 15% gap at 26 knots (Fn=1.0)

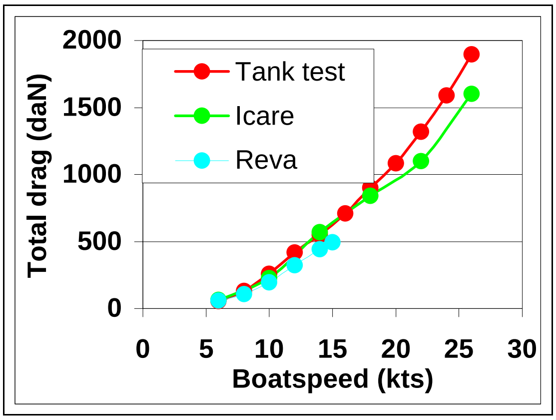

Figure 20 Open 60' upright total drag

Heeled sweep curve, at a 10 knots boat speed, is presented Figure 21. At this speed, viscous drag represents 70% of the total hull resistance. Not taking into account wake effect of transom nor wake vorticity, REVA results are very optimistic where both ICARE and tank test results show that the dramatic reduction of wetted surface with heel is counterbalanced by form factor.

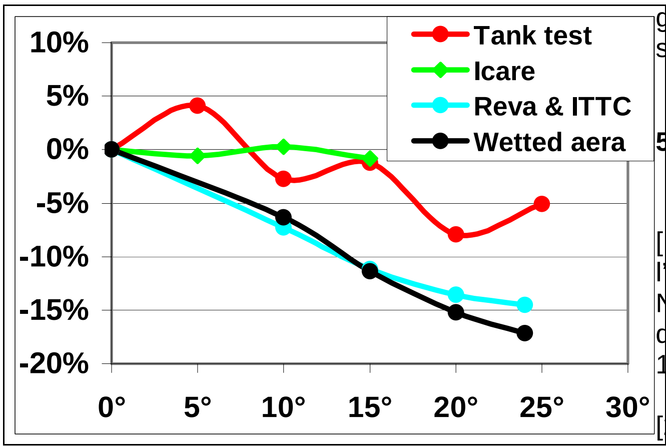

Figure 21 OPEN 60' Heeled drag versus upright drag at BS=10 knots

3. Conclusions and Perspectives

ICARE RANS provide some very interesting improvements relatively to linear potential flow calculation for the study of flow around a hull and for the prediction of hydrodynamic forces. Moreover local variables like shear of velocity flow or helicity can help to control "form factor". We can expect this tool, after further experimental validation to be used for fine resistance prediction as for example hull systematic series study.

Calculations of hull with appendages are already possible but we can expect that size of meshing would become very large to get reliable results for lift and its associated drag. Another ICARE promising application we have started to work on is the calculation of unsteady situations, such as variable boat speed or course. Those problems are up to now out of range of the numerical or experimental evaluation methods used for the design of sailboat, although unsteady efficiency of sailboat such as speed recovering or manoeuvrability become among the main factors of performance at high level like America's cup race.

4. Acknowledgements

Thanks to Bertrand Alessandrini (ECN) for the specific development made on ICARE for sailboat analysis, to Le Defi and to the Yaka Design Team for his stimulation and his confidence, to M. Lombard, J.Berret-O.Racoupeau for the opportunity they have given to test new methods and original design solutions.

5. References

[1] ALESSANDRINI B. Etude Numérique de l'Ecoulement Visqueux autour d'une Carène de Navire en présence de la Surface Libre. Thèse de Doctorat, Université de Nantes, Nantes 1993.

[2] ALESSANDRINI B. DELHOMMEAU G. A fully coupled Navier Stokes solver for calculations of turbulent incompressible flow past a ship hull. International journal for Numerical methods in Fluid vol 29, pp125-142, 1999.

[3] ALESSANDRINI B. DELHOMMEAU G. Viscous free surface flow past a ship in drift and in rotating position. Proceedings of 22nd Symposium of Naval Hydrodynamics, Washington 1998.

[4] DELHOMMEAU G. MAISONNEUVE JJ. Calculation of Flow around several Ship Hulls by a Rankine Source Method, Proceedings of the 2th International Conference Hydrosoft, Southampton, 1986

[5] GERRITSMA J. KEUNING J.A VERSLUIS A. Sailing Yacht Performance in Calm Water and in Waves, Proceedings of 11th Chesapeake Sailing Yacht Symposium, 1993, p 233-259.

[6] PALLU DE LA BARRIERE P. 2000. Optimisation des Performances des Voiliers de Compétition, Journées de l'ATMA, Paris 2000 (on www.craintechnologies.com)

[7] PALLU DE LA BARRIERE P. Vendée Globe 60' : Prévision de Performances et Optimisation, Bulletin CRAIN 1999 (in www.craintechnologies.com)

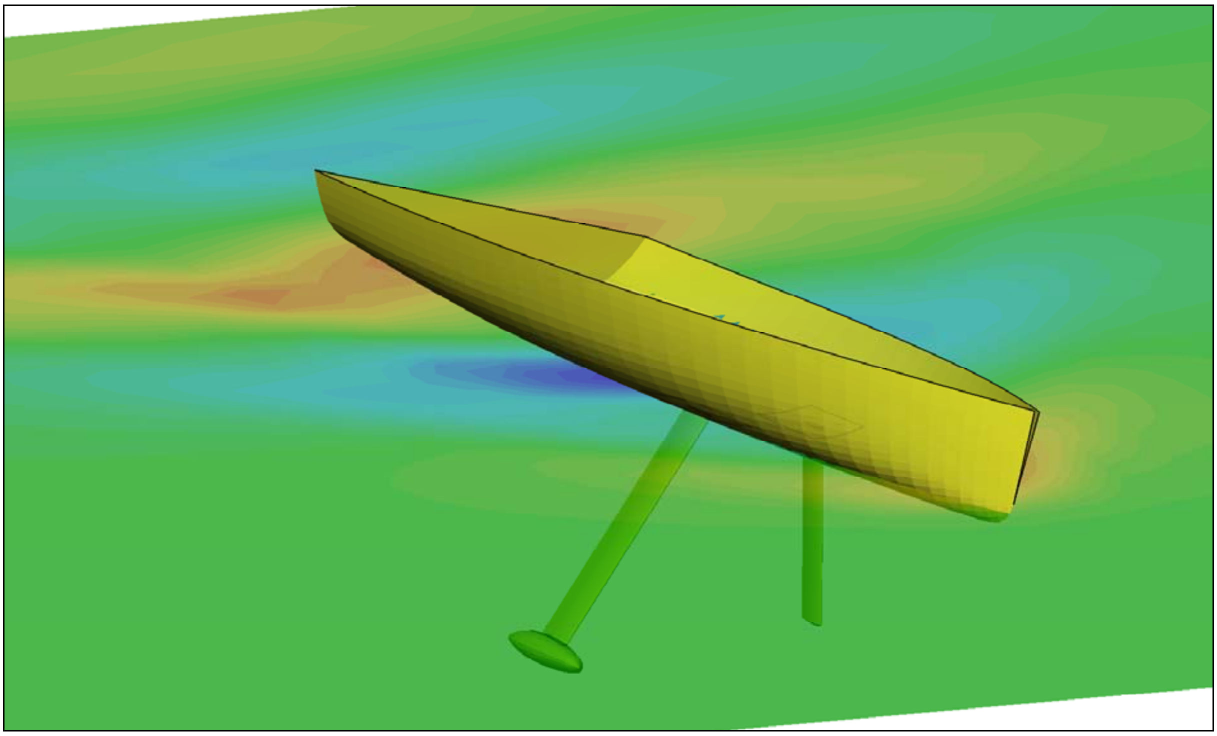

Figure 1 REVA calculation on a OPEN 60’ fitted with canting keel and daggerboard

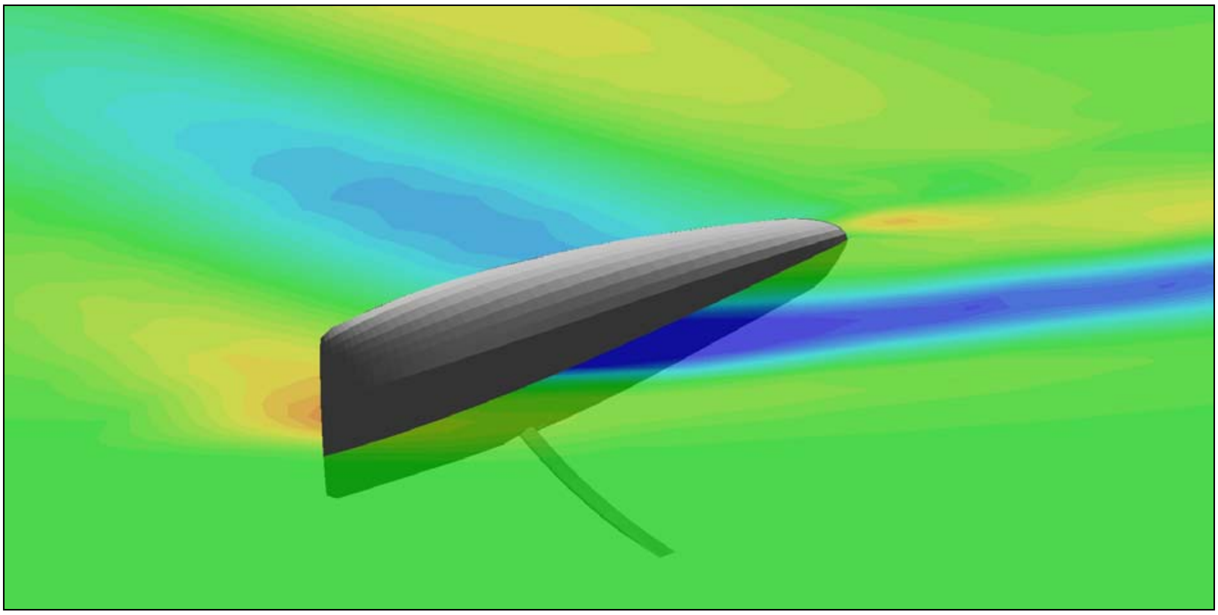

Figure 2 REVA calculation on a multihull fitted with a curved foil

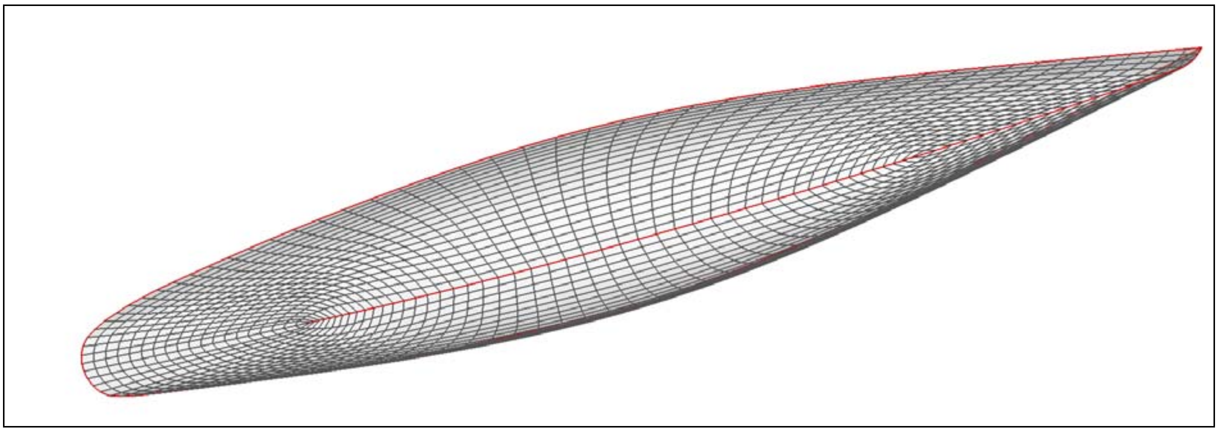

Figure 4 Icare mesh on the hull surface (2000 cells)

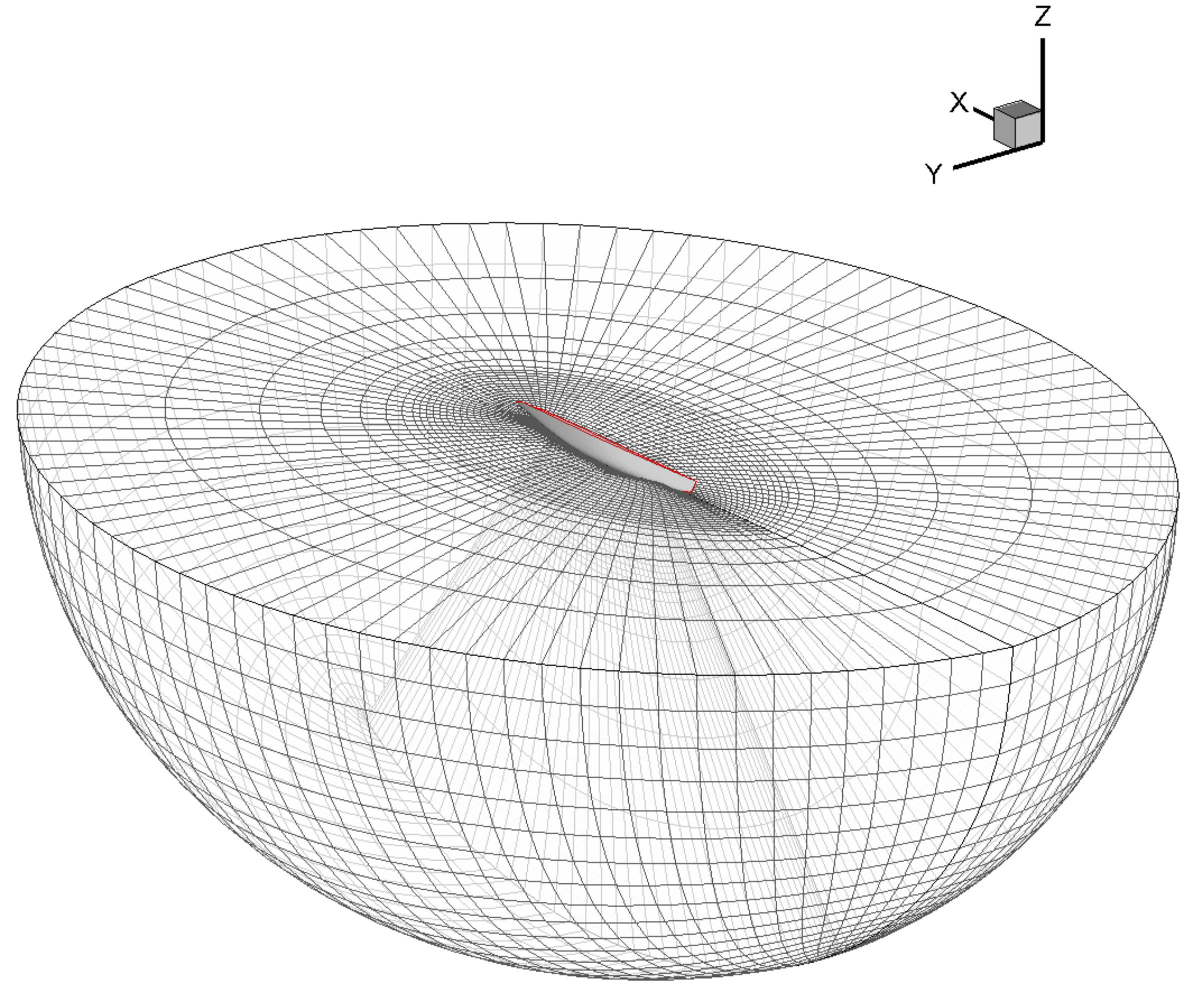

Figure 5 Icare 3D mesh for an ACC hull (80000 cells)

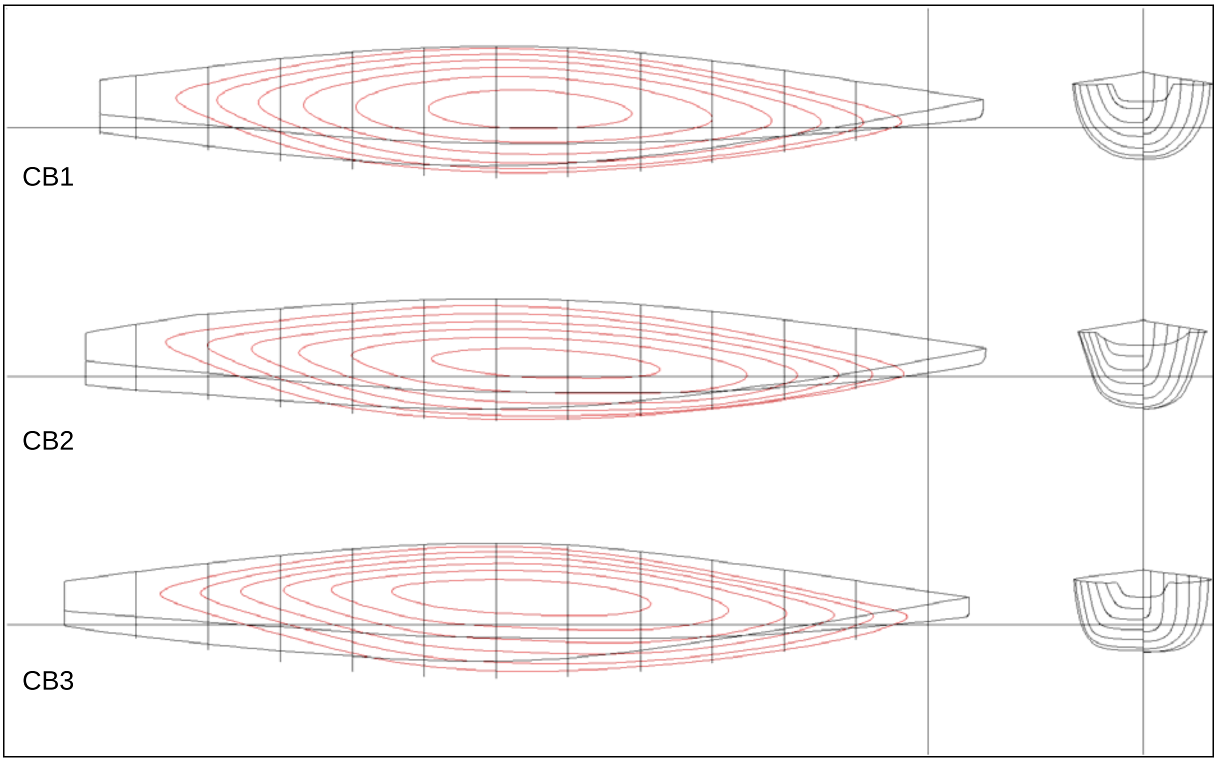

Figure 6 IACC hull body plans and waterline heeled at 30°

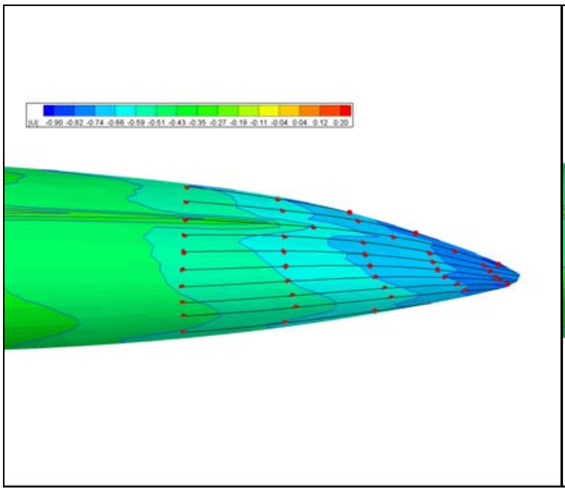

Figure 9 CB1 stern streamlines

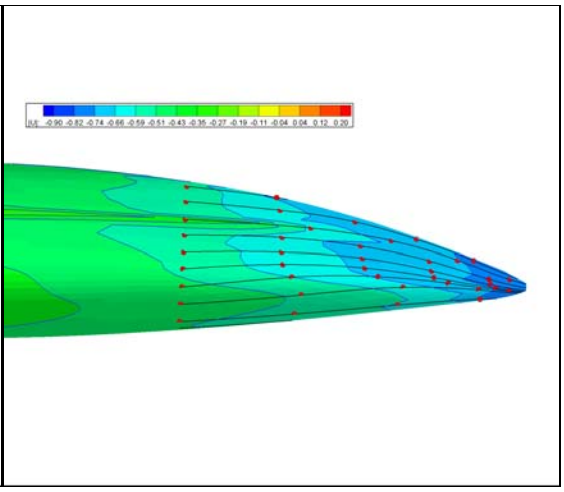

Figure 10 CB2 stern streamlines

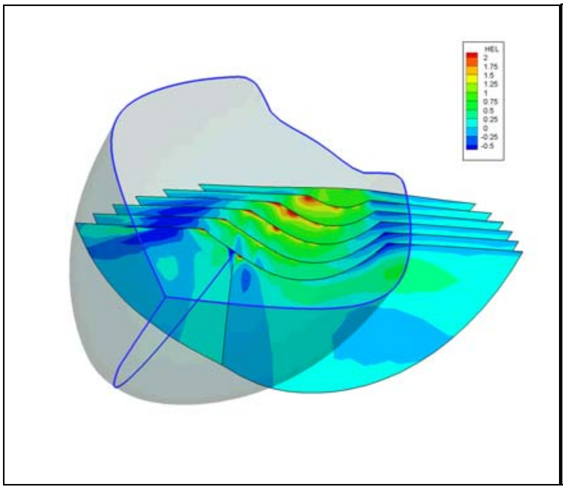

Figure 11 CB1 Helicity at stern

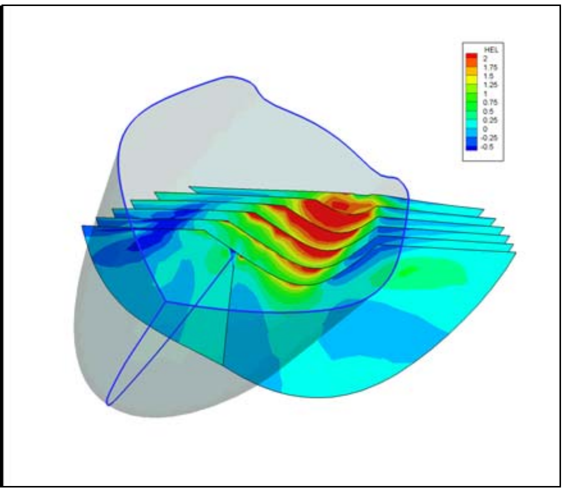

Figure 12 CB2 Helicity at stern

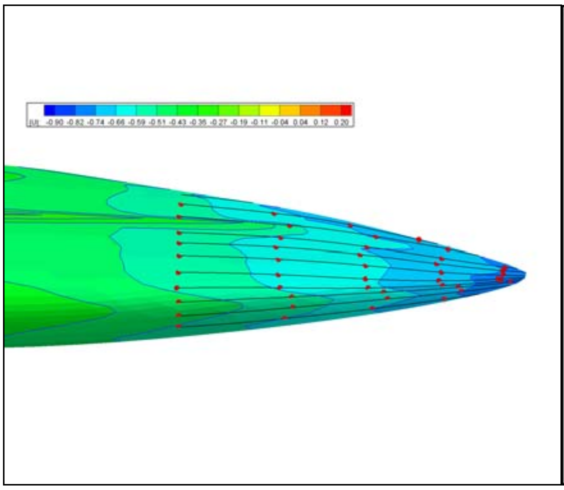

Figure 13 CB3 stern streamlines

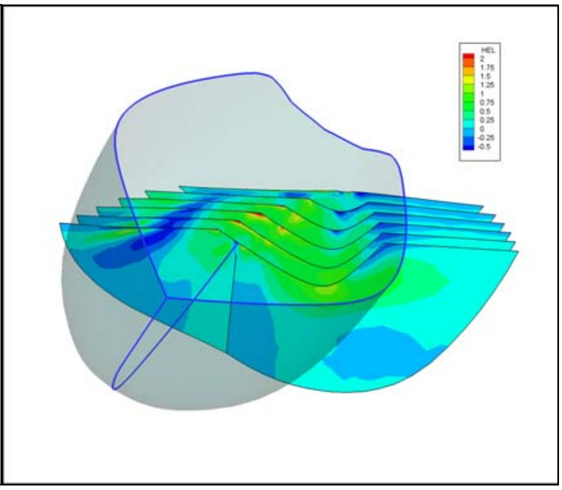

Figure 14 CB3 helicity at stern

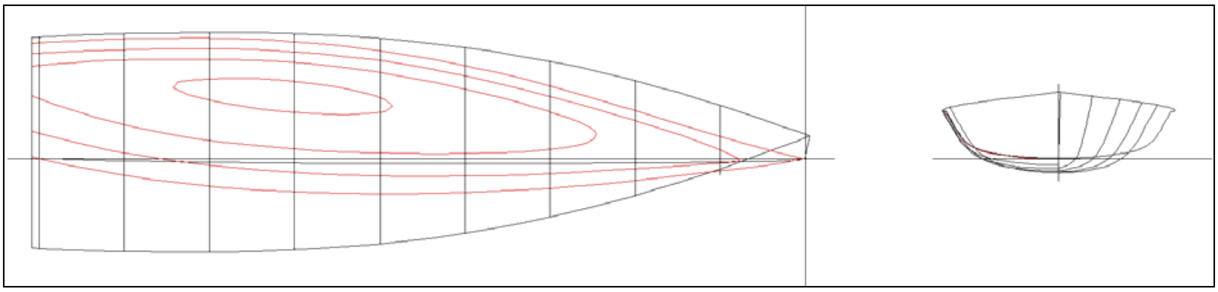

Figure 19 Open 60’ hull body plan and waterline heeled at 20°