Application of RANS to the design of heeled sailboat stern shape

By Philippe PALLU de La BARRIERE, CRAIN [1]

Abstract : The hydrodynamic RANS code ICARE is used to optimize the stern shape of an IACC hull. Influence of helicity and velocity shear is showed.

Introduction

IACC hulls have to comply to design rules which (roughly) bound the upright waterline length LWL and the length of hull girth at the fore an aft termination of waterline. As the hull is heeled when the boat is sailing upright, the designer try to increase the dynamic waterline length and the prismatic coefficient when heeled in order to reduce wave drag without changing the upright static LWL. The main used parameters are the beam, the flair, the slope of keel line at stern and the heeled waterline shape.
Geometric analysis show that :

- Narrower hulls produce longer waterline when heeled but less transverse stability
- Less flair (ie : more vertical hull side) sink more the boat when heeled, increasing the length but decreasing prismatic coefficient.
- Decrease the slope of stern keel line increase the heeled length of waterline but decrease the static waterline for the same measured waterline (see IACC rule to understand subtleties). It also decreases prismatic coefficient and move forward the centre of buoyancy.
- Increase waterline beam, for example using chine, of the aft part of hull between max beam and aft girth increase prismatic coefficient but produce asymmetrical waterlines when heeled.

Hence, find the best trade-off is not obvious even if we consider only steady calm water conditions.
Numerical approach using potential flow with free surface condition and VPP is used extensively since many years and it allows designers to approach trade-off for beam and flair. For the numerical analysis of slope of aft keel line we need an efficient nonlinear free surface condition. Effect of asymmetric waterline on wake can't be analysed by potential flow.

Acknowledgement

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1. Background

Since 1992, CRAIN and the authors used extensively the potential flow free surface code REVA for the study of sailboat hulls and especially IACC hulls. Code REVA is originally

[1] Centre de Recherche pour l'Architecture et l'Industrie Nautiques, La Rochelle, France, www.craintechnologies.com

written by Gerard DELHOMEAU from Ecole Centrale de Nantes (ECN). For the 2000 French America's Cup Challenge, author was involved in the Yaka Design Team in charge of the design of 6th SENS. REVA was used extensively for hull design (see [1],[2]) and tank test validations has showed that some improvements was gotten by this way although not so high than expected by REVA. Hull of 6th SENS was very innovative, the narrower that ever built, having also very sharp chined design at stern to get high prismatic coefficient and longer waterline when heeled. Sailing tests and races have showed that hull was very efficient downwind but did work upwind as properly that we expected. Particularly, the vorticity in the wake seemed intense especially when tacking or pitching.

Still in charge of the design of the IACC boats used by the 2003 French America's Cup Challenge, Yaka Design Team (YDT) had to understand the unexpected behaviour of 6th SENS upwind. First tank test comparison between 6th SENS and smoother shapes as Luna Rossa ITA45 or Team New Zealand NZL60 reconstitutions have showed that although REVA results on the smooth hulls was realistic, REVA results on 6th SENS was very optimistic regarding the tank test measurements. Moreover, Prohaska method show that "form factor" for 6th SENS is higher than for the other hulls.
Since 2000, CRAIN was testing on sailboat hulls a new code, named ICARE, written by Bertrand ALESSANDRINI (ECN). ICARE is a RANS code including free surface effects(see [3]). One of the main expectations of CRAIN team was to prove the ability of ICARE:

- to predict accurately wake turbulence and associated drag.
- to predict accurately effect on drag of the aft overhang.

2. Analysis of ICARE results for two different hulls.

Calculus of viscous flow around several different hulls has been carried out using ICARE. The first test has been made by Erwan JACQUIN from Bassin d'Essai des Carènes (BEC) and followed by extensive calculus carried out by Jerome VEDRENNE (CRAIN&YDT) and Mathieu DORING (CRAIN&ECN). The ICARE results for H0, similar to hull of 6th SENS and for H1 similar to ITA45 and NZL60 show that relative values of calculated drag for H0 and H1 are realistic regarding the tank test measurement of H0 and H1 (Table1).
Following many interesting and impassioned discussions with the hull&hydrodynamic most focused YDT members as Stephan CORDIER (BEC), Peter VAN OSSAANEN, Daniel ANDRIEU, the author has investigated the computed characteristic of the flow in order to find some local criterias.
Two sets of comparative graphics are given below:

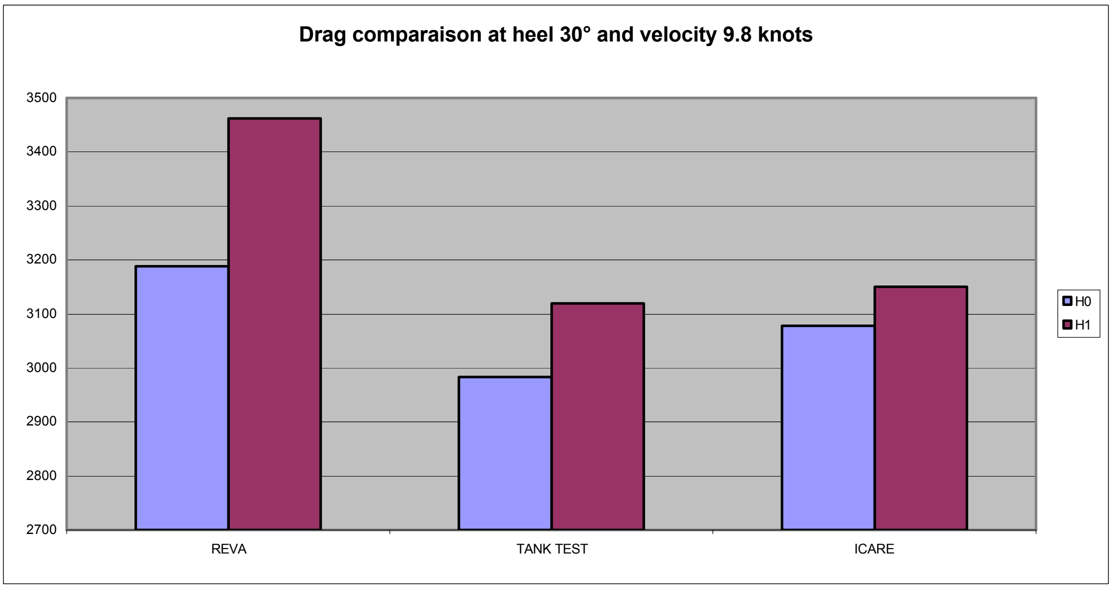
- Graphic 1 shows the velocity of flow along stream line in the aft body part when heeled. Space between black balls render the length that fluid cover for a time interval dt.
- Graphic 2 shows the value of helicity in six transverse planes located near the stern of the hull. Thick dark line is intersection of hull with water surface. Note that intersection of planes with hull give an idea of the chine of H0 sections and of the smoothness of H1 sections.

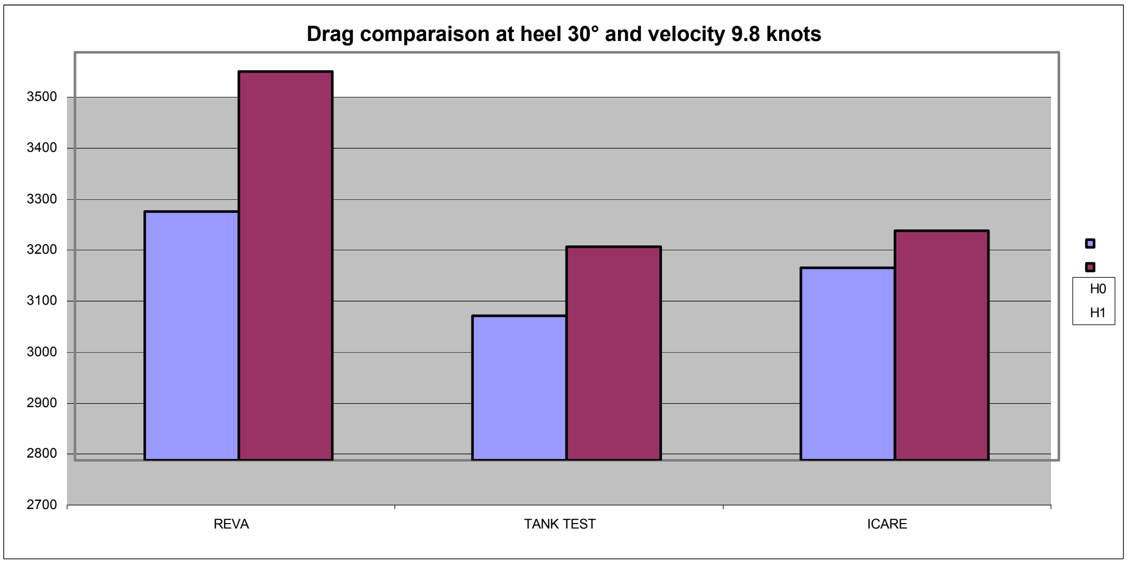
As shown on the following graphics, the flow around H0 heeled has special behaviour regarding H1 flow:

a) Velocity of flow vary a lot when we move along a transverse section in the neighbourhood of stern (Graph1). Flow coming from leeward side is faster than flow coming from windward side.

b) High values of “helicity” [2] occur at neighbourhood of hull stern and of the wake (Graph2).

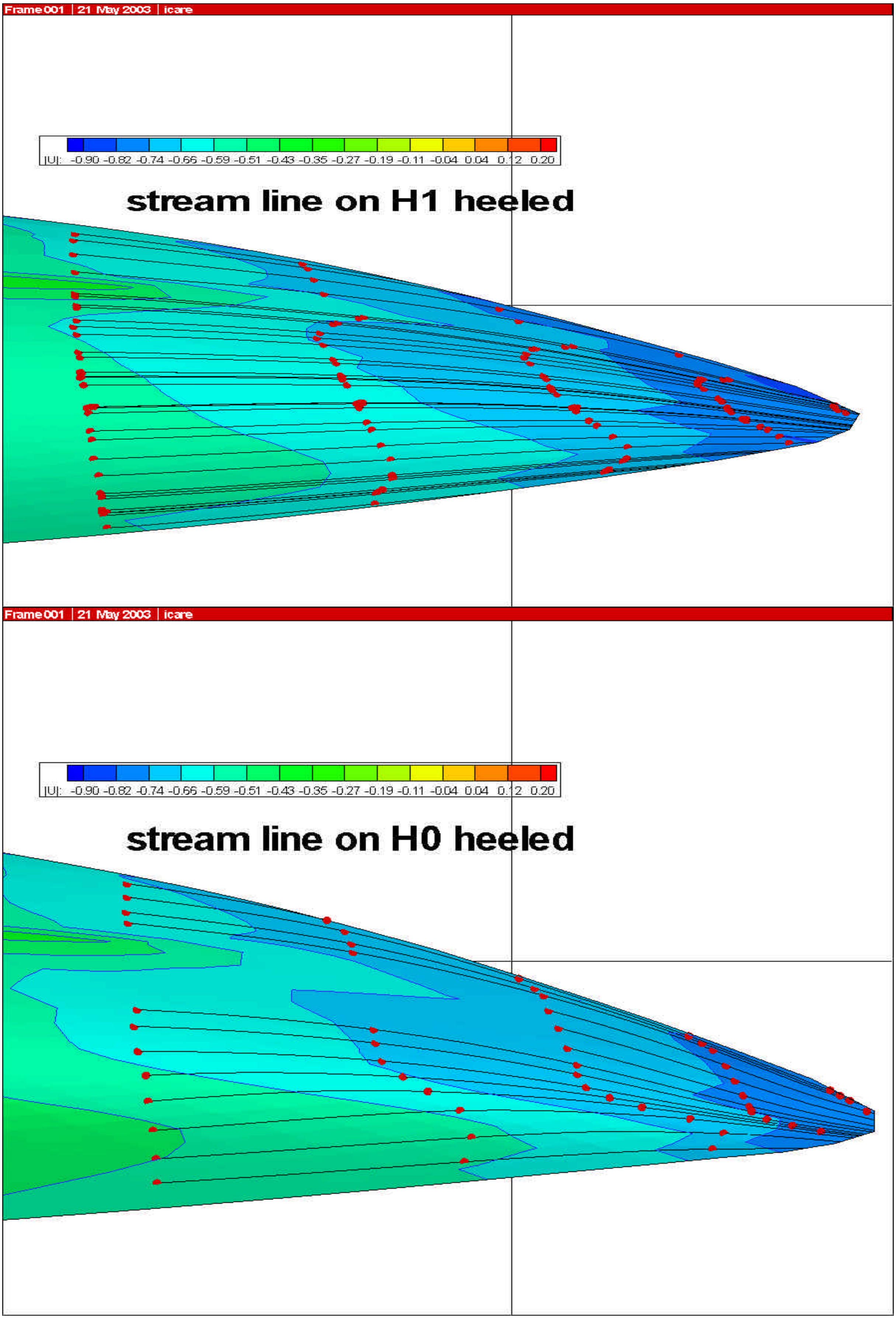
Calculus for other “smooth” hull show same results than for H1 .



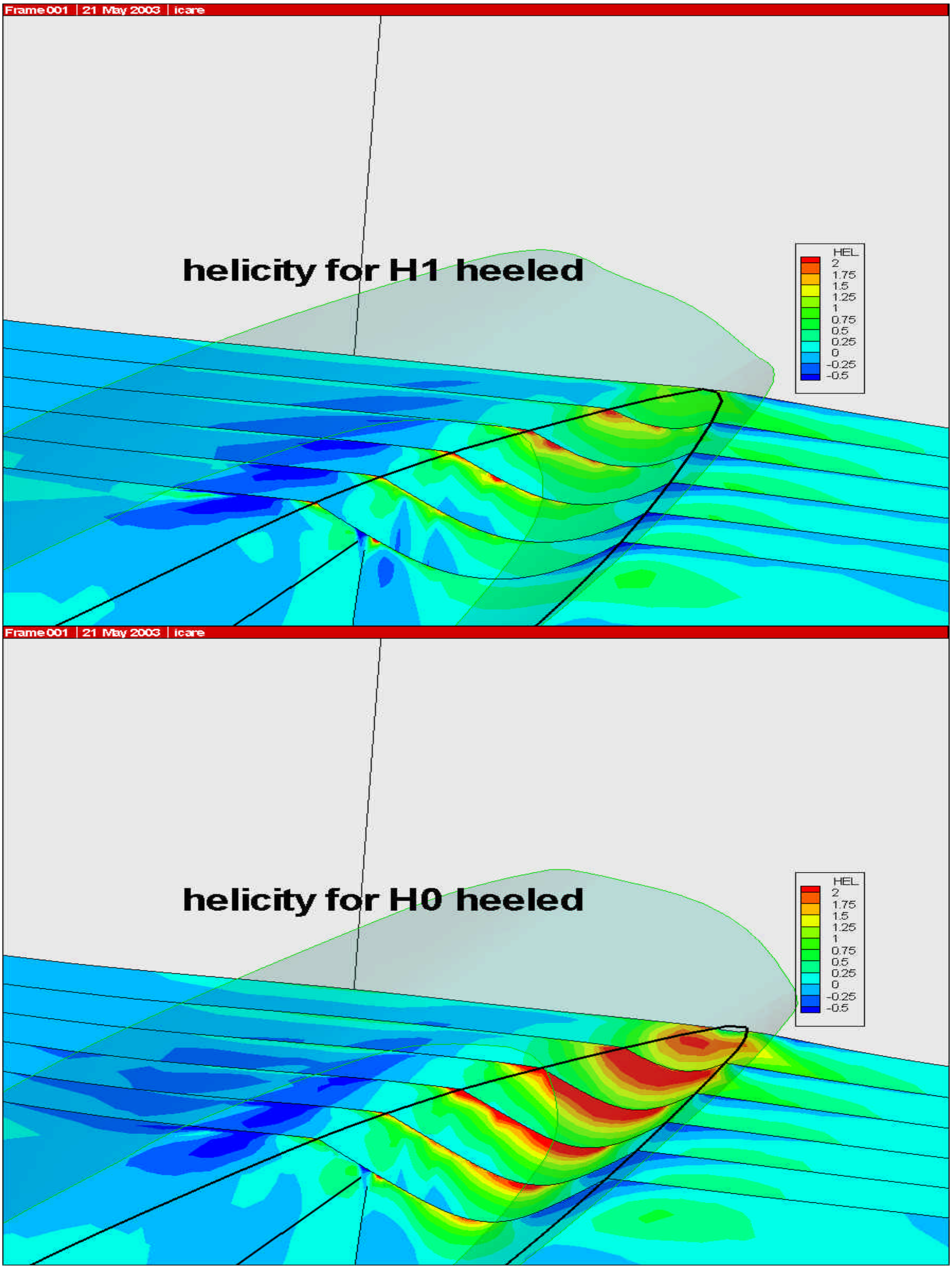


Tab 1 : Drag comparison between H0 and H1

[2] helicity is defined as vector product of curl with velocity field of flow.



Graph 1: velocity of flow along stream line at stern



Graph2: comparison of helicity when heeled

3. Relation ship between velocity shear, helicity and hull form drag.

We can predict intuitively that velocity shear at the stern could produce unstable flow in the wake like a “mixing layer” and as a result, formation of large vortex eddy behind the hull.
Vorticity of flow is related by curl of the velocity field (or by kinematics viscosity). 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 the total 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 quickely. It’s typically vorticity created in the turbulent boundary layer of the hull. Vorticity with helicity correspond to large vortices eddies which are persistent. It’s typically vorticity created by unstable wakes or mixing layer as behind lifting surface (keel) and hull stern. If we look sufficiently far behind the hull, we will see mainly vorticity with helicity because vorticity without helicity has been still dissipated.
Hence helicity seems a good tools to evaluate wake energy ie: form factor.
Those suggestions are based on survey of general fundamental works on turbulence ([4],[5],[6]). I would appreciate very much engineering point of view on this matter!

Conclusion

Using ICARE allow to get some important improvement in the numerical prediction of hull drag especially when nonlinear or viscous effects occur.
Although relationships between velocity shear, helicity and form factor are not formally proven, ICARE analysis shows, for many samples, that some additional drag to regular viscous drag is created by high value of helicity in the aft part of hull. Correlations with tank test results show that RANS calculations with free surface and analysis of local behaviour like velocity shear and helicity could be very useful to predict “form factor” of the hull.

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