Application of a Non-Linear Vortex Lattice Method for Design of Hydrofoil Assisted Catamarans

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1.Introduction

The development of hydrofoil assisted catamarans started in the late 70's with developments in the Soviet Union and in the early 80's with developments in the USA and South Africa. Early developments focused on the design of smaller planing type catamarans with asymmetric hulls using up to three foils mounted in tandem between the demi-hulls. Over the last decade, the application of hydrofoil assistance has extended to include the more modern high-speed semi-displacement type catamarans used mainly for fast ferry applications. While the application of small hydrofoils for these vessels is well known and popular for sea-keeping improvements, the use of larger hydrofoils for improvements in resistance is less well known and is the focus of this paper.

Since the early 80's, the University of Stellenbosch has been involved with development of hydrofoil-assisted catamarans of sizes ranging from 5m to 40m. A practical and successful foil system was patented and named "Hysucat". Hysucats were developed through systematical towing tank tests and planing craft theory. Later a mathematical model was developed using Savitsky's formulations and hydrofoil theory as applied to hydrofoil craft [1,2]. Good results were achieved and later Hysucats were designed and optimized by use of the mathematical model alone without the need for model tests. The experience built up in the design of Hysucats has more recently applied to catamarans with semi-displacement hull forms. A new, patented foil system named "Hysuwac" [3], was specifically developed for larger semi-displacement type catamarans. Application of Hysuwac and other foil systems to semi-displacement type catamarans is still relatively new, with only a hand full of vessels that have been built worldwide.

From such works, enough experience has been built up at the

University of Stellenbosch making it possible, with the aid of the CFD knowledge of the SPbMTU [4], to develop a suitable computational method to aid in the design process and reduce the required towing tank time. As an example of the application and usefulness of the method, the design of Hysuwac hydrofoils for a benchmark size passenger catamaran will be considered. Such a vessel has typical dimensions as given in Table 1. This design was developed by use of the mathematical model for Hysucats [1,2], and systematical towing tank tests at the University of Stellenbosch.

Table 1: Catamaran Main Particulars

Overall Length	Displacement	Installed Power	Speed w/o foils	Speed with foils
40 m	170 t	2 x 2200 kW	36 knots	Approx. 45 knots

Application of the method is described for semi-planing and planing speeds. This covers the design speeds of the vessel with and without foils. This requires one to consider numerical methods that can adequately model semi-planing and planing in combination with hydrofoils. The theoretical method implemented in the commercial package AUTOWING [4], developed at the SPbMTU, is particularly suited to for these types of calculations. Combined with the expertise gained from experimental work, the method was further developed for application to hydrofoil-assisted catamarans.

2. Theoretical method

Hydrodynamically, the hydrofoil-assisted catamaran at high speed can be considered as consisting of two parts: the front foil and the aft hull plus rear foil. The parts are considered separately. The front foil is calculated as a wing moving under the undisturbed free surface. The hydrodynamic effects of the aft hull and rear foil on the front foil are neglected. This has been found to be a valid assumption if the front foil is located forward near the bow. The aft hull and the rear foil are treated as a wing system moving in the vortex-wave wake shed from the front foil. To calculate the wave surface and vortex wake after the front hydrofoil, a three-dimensional Nonlinear Vortex Lattice Method (NLVM) was developed. The intensity of the discrete vortices on the free surface $\vec{\gamma}$ is found from the free surface dynamic boundary conditions (for details see [4]):

$$\gamma_{\zeta} = \left|V^{2}\right| + (\vec{n} \times \vec{\gamma})\vec{V} + \frac{1}{4}\left|\gamma^{2}\right| + 2\frac{y_{w}}{Fn^{2}} - 2V_{x} \quad (1)$$

where γ_z is the component of the vector $\vec{\gamma}$ perpendicular to the speed of the catamaran, $\vec{V}$ is the flow velocity on the free surface, $Fn = V_{\infty}/\sqrt{gL}$ is the Froude number, y_w is the wave ordinate and $\vec{n}$ is the normal unit vector of the free surface.

The velocity on the free surface, $\vec{V}$ induced by the front foil and the vortex sheet $\vec{\gamma}$ can be calculated using Biot-Savart's law. Together with the zero-divergence condition and conditions at infinity,

$$\nabla\vec{\gamma} = 0, \qquad ,|\gamma| \to 0, \quad for \quad |z| \to \pm\infty,\ y_w(+\infty, z) = 0, \qquad \gamma(+\infty, z) = 0 \quad (2)$$

(1) represents a complete system of governing equations for the vector intensity, $\vec{\gamma}$.

In the numerical implementation, the free surface is modeled within a rectangle. As usual in the vortex lattice method, the surface vorticity $\vec{\gamma}$ is represented by a number of closed vortices. Thus, the first equation in Eq. (2) is satisfied automatically in the integral sense. The vector equation (1) is satisfied at the center of each vortex lattice. The vector intensity, $\vec{\gamma}$, necessary for calculations of the RHS of Eq (1) is sought by smoothing the discrete vortices. The kinematic condition on the free surface is used to calculate the shape of the free surface and to adjust the height of the vortex lattice.

The hydrofoil and its vortex wake are treated using the common NVLM method. The numerical instability, which is typical for problems including the dynamics of thin vortex sheets, was avoided using the concept of the cut-off radius. The thickness of hydrofoil is accounted for by a source distribution with strength equal to the thickness gradient in downstream direction.

The calculation of the hydrofoil under the free surface is performed using a special iterative technique. Even if linear version of the boundary condition (1) is used, the iterative technique is necessary because the position of the vortex wake is a very important factor affecting the wave deformation and it can only be found iteratively.

The calculation of the hull is done by assuming planing conditions. This makes the method valid for the upper end of the transition phase and higher. The planing hull moving in the vortex wave wake of the front foil is based on the wing analogy discovered by Wagner. Each lifting surface is represented via a set of thin cambered longitudinal strips with rectilinear leading and trailing edges. Such an approximation allows one to model planing surfaces and hydrofoils with curved leading edges, including warped hulls with variable deadrise. If the wetted area of the planing surface is known, the pressure distribution and forces are obtained by using the conventional Vortex Lattice Method (VLM).

A special technique, which in its idea is very similar to the simplified method described in [5] for two dimensions, is applied to estimate the wetted area of a three dimensional planing surface with an arbitrary length to beam ratio. This method is rather simple and can be written in a general form that covers complex planing geometry moving in the vortex-wave wake.

3. Selected results of numerical investigations

The developed method was used for the investigation of hydrodynamics of a Hysuwac type Hydrofoil assisted catamaran with particulars as given in Table 1. The investigation was directed at finding the optimal way to retrofit existing catamarans with hydrofoils. Focus was therefore on investigating different foils and the mutual position of the foils and the hull, while not changing the hull geometry.

The numerical calculations showed that among the geometric parameters investigated, the most effective tool to optimize the catamaran is the lateral distance between the foils. The effect of other parameters was comparable with the accuracy of the numerical approach. The calculation included both the determination of the hydrodynamic forces and attitude of the ship.

Figure 2 displays results. Three different cases, schematically sketched in the Fig.1, are considered. Firstly, the basic variant of the Hysuwac arrangement (Case 1), secondly, the same arrangement but with the rear foil shifted towards aft by 3 m (Case 2). Finally, the arrangement of the Hysuwac with hull and the rear foil shifted aft by 7 meters with respect to the front foil or, in other words, the front foil shifted forward towards the bow by 7 m (Case 3). A clear tendency emerged: that increasing the distance between foils results in an improvement of the L/D ratio. As seen in the figure, the best case is the Case 2, followed by Case 3 and then the Case 1. To explain this result, consider Figures 3-5 illustrating the three results obtained for the center of gravity position at the point securing the best L/D ratio for given weight: 170 ton at a speed of 40 knots.

As seen from the Fig.3, the larger the distance, between the front foil and the rear foil, the larger the up wash induced by waves. The reason is clear. In the first case the rear foil is located close to the wave trough. The foil located behind the wave trough utilizes the positive up wash induced by waves. That is why the lift coefficients of the rear foil and the rear lifting system (the rear foil+hull) are the maximal for Case 3. Because the lift and the L/D ratio are increased when we shift the rear foil aft, the L/D ratio is larger for Cases 2 and 3 than for Case 1.

The increase in lift of the rear lifting system leads to the ship rising further out of the water. The wetted area is decreased being minimal for Case 2 (see Fig.4). The increase of lift leads to a decrease of the pitch angle and consequently the lift of the front foil. Therefore, the intensity of the tip vortex shed from the front foil is also decreased, weakening the downwash induced by the tip vortex on the rear foil (see Fig.5). Again, it leads to an increase of the lift on the rear lifting system. Despite of the fact that the lift decreases with decreasing pitch angle, the lift of the rear lifting system becomes larger. The two effects increasing the lift (i.e. less downwash induced by the weaker tip vortex and increased up wash induced by wave crest) prove to be stronger effects.

Because the wetted area is maximal in Case 3, this arrangement has the largest fraction of the hull friction resistance. This is why the L/D ratio of Case 3 is less than that of Case 2. However, the positive influence of shifting the front foil forward resulting in higher lift for the rear lifting system proves to be sufficient to improve the L/D ratio of Case 3 compared to that of Case 1. Comparison of computed results with experiments for the basic variant showed that the overall resistance prediction is within 5% of measured values.

The first tendency observed by shifting only the rear foil aft in Case 2 was clearly confirmed in the tests performed at the University of Stellenbosch. The second tendency found in Case 3 (shifting the front foil towards bow) is rather an unexpected one because, as a rule, an increase in wetted area of that magnitude leads to an overall increase in resistance. Therefore, the result presented here, is material for discussion and needs further experimental investigations.

At present, the authors are working on a NLVM method for 3D planing problem generalized for small Froude numbers accounting for the gravity effects.

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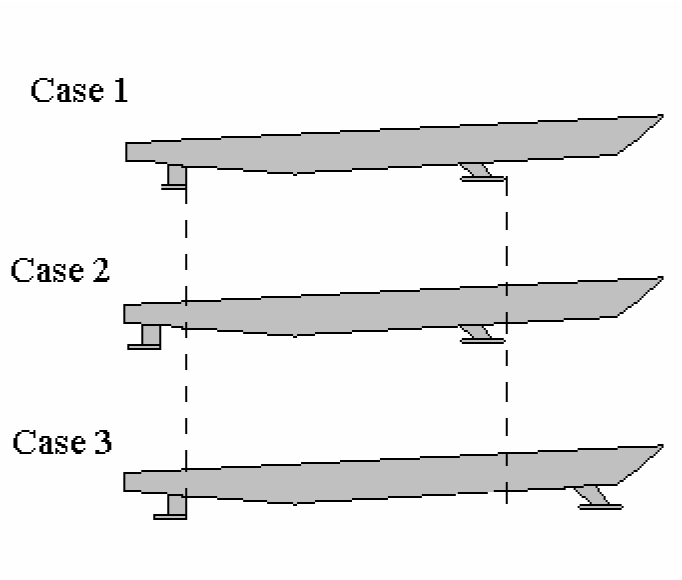

Figure 1: Schematic sketches of the arrangement in three cases

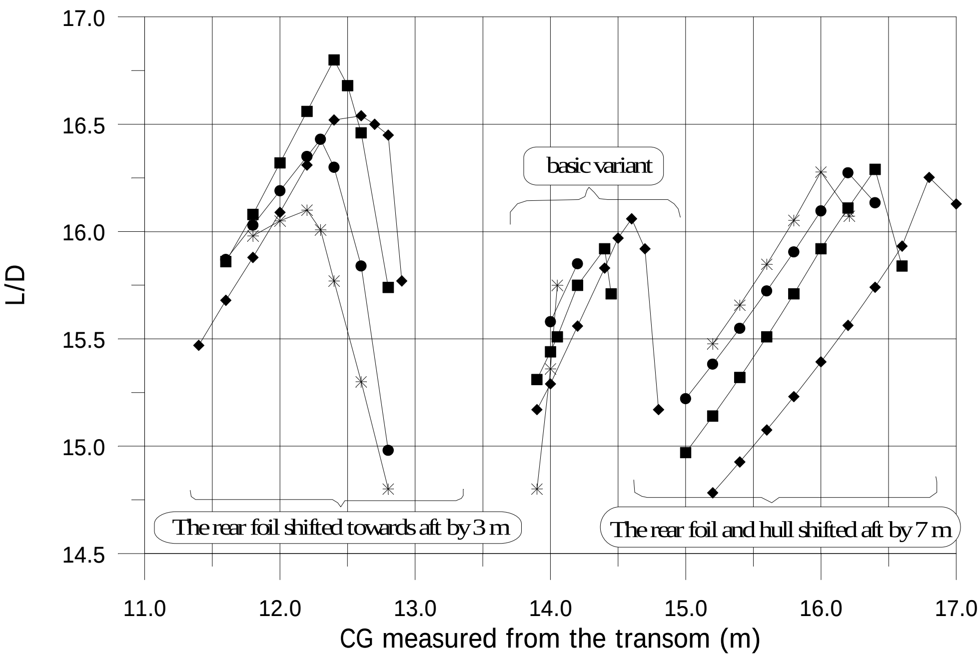

Figure 2: The L/D ratio versus the position of the center of gravity for three cases . The wave resistance is not taken into account. Diamonds- 170 t, bars- 180 t, circles- 190 t, stars- 200 t

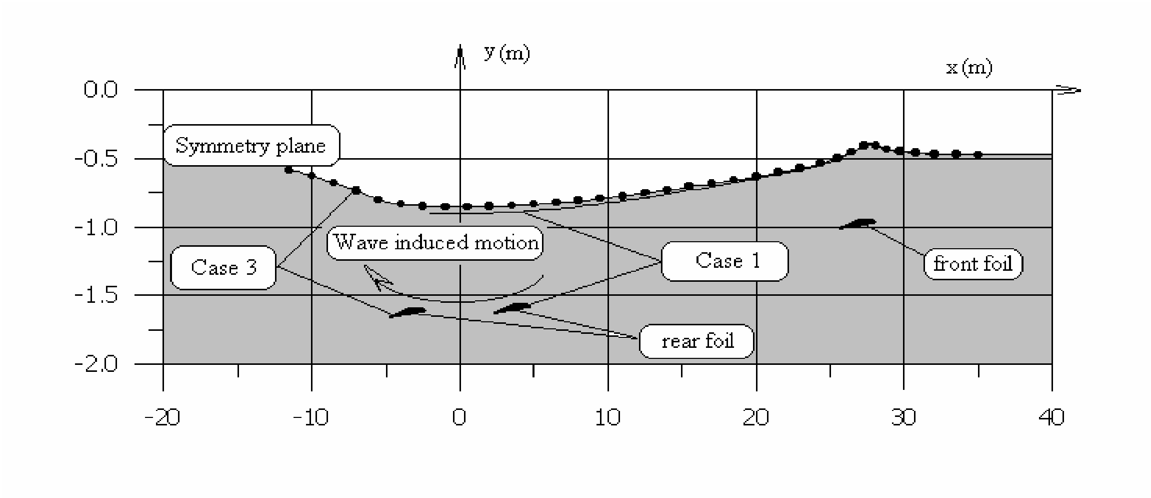

Figure 3: The mutual positions of the rear foil and the wave surface at 40 knots.

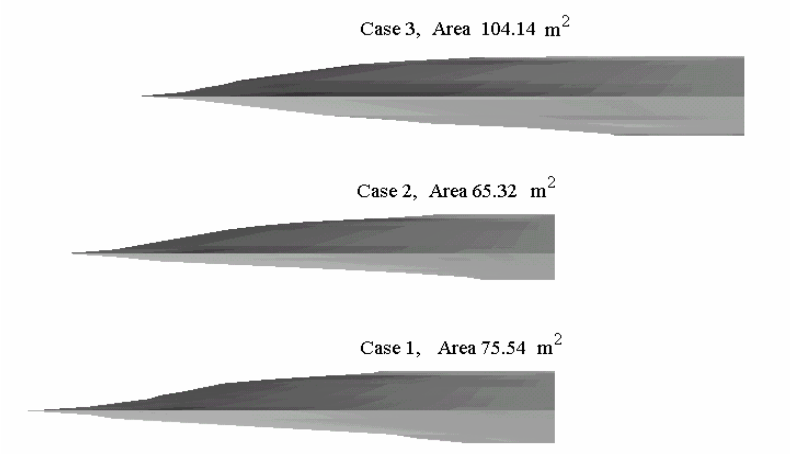

Figure 4: Wetted area of the catamaran hull for three cases.

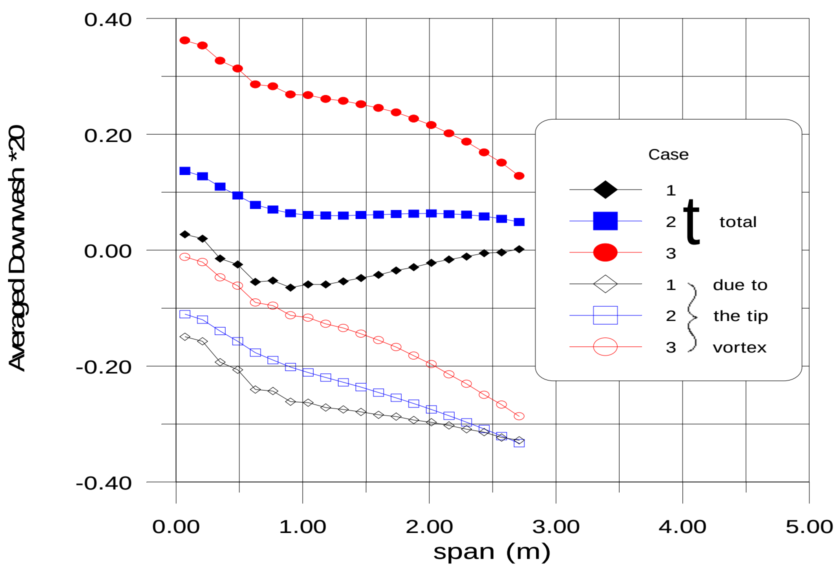

Figure 5: The downwash (up wash if positive) averaged along the chord B.