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YACHT PERFORMANCE PREDICTION : TOWARDS A NUMERICAL VPP

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Abstract. The coupling of aerodynamic computations of the flow around the sail and hydrodynamic computations for the flow around the hull of a sailing boat is achieved in order to predict its performance in calm water. The aerodynamic code is based on a lifting surface model for the sails and a vortex method for its wake. The hydrodynamic one is a Boundary Element Method using the steady wave resistance Green's function with a particular attention to the accuracy of the computations of the various boundary integrals involved. The motion of the sailing boat upward is studied by computing the horizontal acceleration at each time step and then deducing the velocity and position of the boat. The heel balance is performed in a very simplified model: the aerodynamic rolling moment on the sails is balanced by static moments, due to the keel mass and the crew one, assumed to be located at a certain distance off the symmetry plane of the boat. Different options of these calculations are available: the heel angle is fixed and the weight of the crew located on one side of the boat can vary; it is also possible to give a maximum value to this crew mass and let a free heel angle; the last option is to let a fixed crew weight and free heel angle. Results are presented only in steady flow.

1. INTRODUCTION

The prediction of sailing yacht performance involves a large number of parameters, the action of which is far from being fully understood even with the help of the more recent theoretical and experimental techniques. Because of this complexity, the development of prediction code was essentially based on large data bases collected from various existing boats together with a multidimensional interpolation process. The emergence of such VPP codes at the end of the previous century (see for example Larsson [1] or Schlageter & Teeters [2]) was probably a major step although it was constitutively limited to boats that lie inside or are very close to the domain defined by those which were used to build the database. An other important feature of the method is that hull sails have to be separately evaluated, whereas their interaction reduces to a simple balance between aero and hydrodynamic estimated forces.

The constant progress of computational fluid dynamics had brought the simulation of the flow about hulls and sails for a sailing boat to a level which makes it possible to envisage the building of a numerical tool providing, in the long term, a useful tool for designers. One of the mayor difficulties of such a computation is that the flow over any one of the components – sails and hull – operating in real sailing boat is a very complex combination of many phenomena, some of which being clearly non-linear. Beside this, a sailing boat is an integrated system in which sails and hull closely interact. Therefore, research has to be conducted not only to improve the description of each isolated element, but also to describe the interaction effects. Using the best available modelisation for each part of the system – probably something like unsteady Navier-Stokes solvers – would unavoidably yield a huge problem with CPU time requirement exceeding any computational power today available.

As usual, simplifications have to be introduced and, as much as possible, justified a priori in order to keep the CPU time within acceptable limits. Regarding the sail-hull interaction, a lot of recent progress has been obtained by considering that the whole system behaviour can be described by some non-linear tool such as dynamical system or neural networks. One important advantage of this approach is that it starts from real life data rather than simulated data allowing to account for the totality of the phenomena involved.

In the present work, we start from the other end considering only numerical models as basic ingredients. In this approach, the validity of the resulting "virtual sailing boat" is only verified once favourable comparison with real life data has been established. It is however a necessary step if one wants to derive a self consistent numerical model for sailing boats which is actually our goal in the long term.

As mentioned before, restrictive assumptions are still necessary if one want to build any tractable model. We have assumed that the interactions between sails and hull can be conveniently approximated by means of linear

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models, although the sail model or hull model used can be non-linear. Thus the resulting sailing boat model will be non-linear as well.

The hydrodynamic problem is solved by means of a boundary integral method by Boin [3], Ba & al. [4], developed both for wave resistance and seakeeping problems in the frequency domain. Only the wave resistance and lifting problem version of the code is used in the present work. The wave resistance calculations uses the wave resistance Green function as the limit, as the frequency tends to zero, of the diffraction-radiation with forward speed Green function. It is well know that the Green functions for these problems have a singular behaviour which requires the introduction of particular techniques. In order to solve this problem the integral equation is based on a velocity formulation. To take into account the lifting effects, a Kutta-Joukowsky condition is imposed downstream of the trailing edge of the lifting parts of the hull. The discrete equations are obtained through a first order panel method in which the contribution of each panel has been computed using a constant singularity distribution and the exact panel geometry. The main feature of this code is to interchange the boundary integration (on hull panel, on waterline segment or on semi-infinite strips extending from the trailing edges of the lifting parts of the hull, due to the discretisation of the 3rd Green identity), and the Fourier integration due to the Green function or its derivatives. The first integrals are calculated analytically using the Stokes theorem and the Fourier ones are computed by an Adaptive Simpson method enabling to decrease the integration step when the integrand becomes oscillating. It has been shown that this technique gives accurate integration with a moderate computational time, except when the source and field points are on the free-surface. This case appears only when it is required to compute the free surface elevation. The method can be used either with the wave resistance Green function or with the diffraction-radiation with forward speed one.

Concerning the aerodynamic calculations, we use a flow description by means of lifting surfaces for the sails and particle method for its wake (Charvet & al.[5,6], Hauville [7]). In order to satisfy at every step, a condition formally derived from the Joukowsky condition at each time step, emission of particles is performed along given lines (sail trailing edges). The Biot-Savart relation is used to calculate the velocity field of the particles; finally, the deformation term is calculated by an integral relation obtained after having differentiated the Biot-Savart law.

In the present study, only the motion of a boat sailing up-wind (apparent wind angle less than 70°) in order to avoid any separation of the flow on the sails, these sailing conditions ensure that the actual aerodynamic incidence of the sails never exceed 10°, is considered. At each time step, we compute the forces and moments on the sails and the boat attitude, from which forces on the hull are obtained by interpolation in tables a priori done and calculated,. Then boat acceleration is computed from the solution of Newton's equation and by integration, boat velocity and attitude are estimated from the acceleration by the Adam Bashforth integration scheme. Examples of results obtained for a First class 8 sailing boat in steady flow are presented.

2. HYDRODYNAMIC CALCULATIONS

2.1 Problem to solve

A frame of reference Oxyz fitted to the body is used with the origin O on the undisturbed free-surface, x axis pointing in the direction of the boat motion, assumed to be with a constant velocity, and z axis is vertically positive upwards. With the assumptions of inviscid and incompressible fluid and irrotational motion except on some surfaces, the velocity potential can be used. It satisfies the Laplace equation in the fluid domain, the linearized free surface boundary condition, the radiation condition and suitable conditions at infinity. After use of the third Green's identity, the body condition leads to the following equation after an appropriate choice of the inner potential on the body S, with C is the waterline:

$$\forall M \in S \qquad \frac{s\,(M)}{2} - \frac{1}{4p}\iint_S s\,(M')\frac{\partial G\,(M,M')}{\partial n_M}dS_{M'}$$
$$+\frac{U_\infty^2}{4p\,g}\int_C s\,(M')\frac{\partial G\,(M,M')}{\partial n_M}(\vec{n}_{M'},\vec{x})dy_{M'} \qquad (1)$$
$$-\frac{1}{4p}\iint_{S_1\cup S_2\cup\Sigma} m\,(M')\frac{\partial^2 G\,(M,M')}{\partial n_M \partial n_{M'}}dS_{M'} = \frac{\partial \Phi_e}{\partial n_M}$$

where $\vec{n}_k$ is the outward unit normal to the wake. The Kutta-Joukowsky condition is applied by assuming that a very small distance of the trailing edge, the velocity is parallel to the direction of the bisecting line of the trailing edge angle. The doublet distribution with intensity m is distributed on the projection of the body on its plane of symmetry S_1, on the projection of the lifting part of the hull S_2 and on a wake extending from the trailing edge of the hull to downstream infinity. The Green function, obtained by taking the limit for the frequency tending to zero of the ship motion Green function is giving by, following Delhommeau [8]:

$$G_s(M,M') = G_0(M,M') + Gw(M,M'); \qquad (2)$$

$$Gw(M,M') = \Re\left\{\frac{-2}{p\,Lo}\int_{-p/2}^{p/2} K_s g_1(K_s x)\,dq\right\}$$

$$G_0(M,M') = \frac{1}{Lo^2}\left[\frac{1}{\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}} - \frac{1}{\sqrt{(x-x')^2+(y-y')^2+(z+z')^2}}\right]$$

In this equation g_1 is a modified complex integral function defined by: $g_1(x) = e^x e_1(x)$, with $\varepsilon_1(\xi) = E_1(\xi)$ if $\Im(x) \geq 0$; $\varepsilon_1(\xi) = E_1(\xi) - 2i\pi$ if $\Im(x) < 0$. E_1 is the complex exponential integral function of order 1 defined by:

$$E_1(x) = \int_x^{\infty} \frac{e^{-t}}{t} dt \quad \text{if} \quad -p < \arg(x) < p$$

$E_1(x) = \int_1^{\infty} \frac{e^{-xt}}{t} dt, \quad \text{if } \Re(x) > 0$. The pole K_s is defined by $K_s = \frac{1}{F^2 \cos^2 q}$, with:

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \frac{1}{Lo}\left\{ z + z' + i\left[(x - x')\cos q \pm (y - y')\sin q \right] \right\}$$

$\Re$ and $\Im$ represent real and imaginary parts. Another form can be obtained by using the function G'_0, where a + replaces the minus sign – in the square brackets, so:

$$G_s(M,M') = G'_0(M,M') + Gw_2(M,M');$$
$$Gw_2(M,M') = \Re\left\{ \frac{-2}{pLo} \int_{-p/2}^{p/2} K_s \left(g_1(K_s x) - \frac{1}{K_s x} \right) dq \right\} \quad (3)$$

Both forms are used alternatively.

2.2 Discretisation and numerical solution

The body surface S and surfaces S_1 and S_2 are divided into plane quadrilateral panels where the source and doublet intensities are assumed to be constant. Consequently the waterline is divided into segments where the source intensity is also assumed to be constant and taken equal to the value of the closest panel. The wake is divided into strips. The Kutta condition is applied to points located slightly downstream of the trailing edge at distance dds. On S_1 and S_2, an x-evolution law for the doublet intensity has been chosen.

By discretising eq. (1), integrations of the Green function and of its derivatives have to be performed on panels, segments or semi-infinite strips. These are performed after having interchanged the boundary and Fourier integrations. The first ones are performed analytically, following Bougis [9], by the use of the Stokes theorem:

$$I_s = \iint_s \frac{d^2}{dc^2} f(c)\, ds' = \sum_{k=1}^{m} C_k \frac{f(c_{k+1}) - f(c_k)}{c_{k+1} - c_k}$$
$$c_k = \frac{K_s}{Lo}\left[z + z'_k + i\left[(x - x'_k)\cos q + (y - y'_k)\sin q \right] \right]$$

For example, using eq. (2), the boundary integration on a panel for the Froude number dependent part of the Green function can be written as:

$$\iint_S Gw\, ds' = \frac{-2}{p}\Re\left\{ \int_{-p/2}^{p/2} \sum_{k=1}^{m} C_k D_k\, dq \right\}, \quad D_k = \frac{\left[\iint g_1(x) \right]_{c_k}^{c_{k+1}}}{c_{k+1} - c_k} \quad (4)$$

The same method can be applied for the integration on the waterline segments. The panel method involves also integrals of the second derivative of the Green function in the wake extending from an element of the trailing edge. Difficulties appear for $q = p/2$ or $-p/2$. The integrand has no finite limit as q tends to $p/2$ and $x' \to -\infty$. The integration of the Rankine term is well known, see for example [8]. For the wave term Gw_2, (here, Green function given by eq. (3) is more appropriate) the wake is decomposed into a quadrilateral panel Σ_0 and a semi infinite strip Σ_1 with doublets, with a vertical leading edge. Detail can be found in [3]. It can be found in [3] or Boin & al. [10], a study of the convergence of the present method and various cases of validation and applications.

2.3 Results on the First Class 8 hull

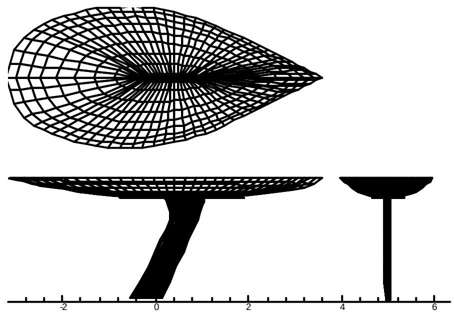
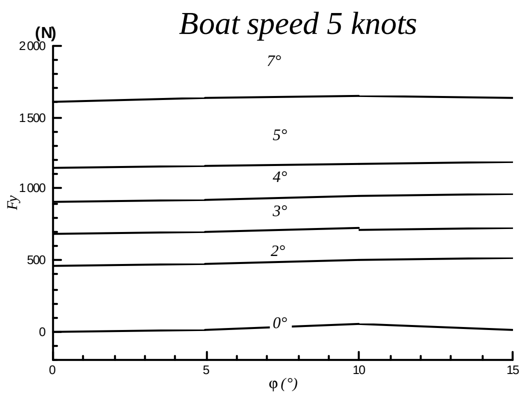
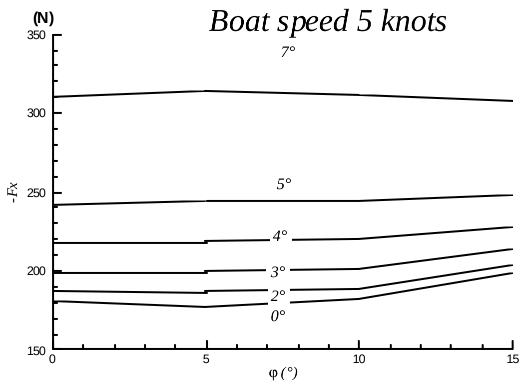


Figure 1 : Definition of the First Class 8 hull



a) Side force



b) Total drag

Figure 2 : Variation of forces versus the heel angle j for various yaw angles for the First Class 8 hull

The sailing boat Bénéteau First Class 8 has been designed by the naval architects Jean-Marie Finot and Jacques Fauroux. The main characteristics of the hull are the length on waterline L=6.75m, the displacement

Δ=1835kg (including 600kg for the keel and 391kg for the crew) and the draft T=1.8m. The hull wetted area is 10.5m² and the keel area is 2.06m². We have used a grid of 960 panels for the hull and a grid of 10 strips of 20 panels for the keel, figure 1. To obtain a good convergence of the results for the Fourier integrals, the body has been slightly submerged to z=- 0.05 m.

Wave drag has been computed for boat speed from 0 to 6 m/s (F=0 to 0.7), with yaw angle a ranging from 0 to 10° and for the heel angle from 0 to 15° by a step of 5°, assuming symmetry with respect to zero heel angle. The formulas used to calculate the viscous resistance is derived from the ITTC1957 formula:

$$Rf = \frac{1}{2} r_w U^2 Sm Cf\ ,\quad Cf = \frac{0.075}{\left(\log R_L - 2\right)^2}\ ,\quad R_L = \frac{U.L}{u}$$

Rf is the viscous resistance, Sm the total wetted surface and Cf is the local friction coefficient calculated using the Reynolds number R_L with u=1.1610^{-6}m^2/s. r_w is the water density.

Figure 2 shows the side force (graph a) and the total resistance (graph b) versus the heel angle j for various values of the yaw angle, for a boat speed of 5 knots. It can be shown that Fy increases with the yaw angle but is quite constant with the heel angle. Concerning the total drag, -Fx increases with the yaw angle; the variation with the heel angle is more complex: it is quite weak, except for low yaw angles (a≤4°) where it can be observed than for j>10°, the total resistance increases with the heel angle.

3. SAIL AERODYNAMIC COMPUTATIONS

3.1 Method of computation

Sail modelling actually involves many different aspects: the flow is mainly dependent on the sail shape which is the result of the balance between the aerodynamic forces and the internal stresses within the sail structure, which can be very complex in recent sails. The aerodynamic force prediction requires the simulation of the flow around the sails. Because of their very small relative thickness, sails are probably best analysed using the lifting surface approximation. This provides the basis of our flow modelisation which has been otherwise considered as a fully non linear problem. This is an absolute necessity if one wants to conveniently represent the effect of the boat motion at the higher sections of the sails.

The method chosen for the calculation of the flow around the sails is the vortex element method (VEM), often used for external flows with bounded vorticity support. For the lifting surfaces, the turbulent shear layer along the sails is represented by a dipole surface distribution and the wake formed by the vortex shedding along the trailing edges is represented by vortex sheets. During the last ten years, this method was successfully validated, particularly to capture dynamic wake effects in details [5 to 7]. This problem is split in 2 parts, a lifting body problem and a wake one, coupled by a kind of Kutta condition derived from the kinematic and dynamic conditions along the separation lines, chosen here as the sail trailing edges. The flow is assumed to be inviscid, except when writing this Kutta condition. The lifting problem is solved by means of a first order boundary integral method. The sail surfaces are divided into quadrilateral panels. To satisfy the body condition, the dipole strength associated with each panel is used in order to have a normal velocity null at collocation points. The wake is modeled by means of the vortex method itself, so the vorticity distribution on the wake is described by means of particles carrying vorticity. Their motions are computed in a Lagragian framework and the vorticity on each particle has to satisfy the Helmholtz equation. According to the Helmholtz decomposition theorem, the velocity field is given by:

$$\vec{U} = \vec{U}_\infty + \vec{U}_w + \vec{U}_f + \vec{U}_{ext}$$

where $\vec{U}_\infty$ represents the inflow velocity; $\vec{U}_f$ and $\vec{U}_w$ are derived from a scalar potential f and from a potential vector $\vec{y}$, representing respectively the body's and the wake's influences; $\vec{U}_{ext}$ is the velocity field induced for example in the wake of an another lifting body. We use the Euler equations in velocity-vorticity formulation for a particle i expressed in Lagrangian coordinates. $\vec{X}_i$ is the geometric centre of the particle, the center of gravity of the vorticity contained in the particle or any other point representative of the particle location. $\vec{\Omega}_i$ is the amount of vorticity contained in the particle:

$$\vec{\Omega}_i = \iiint_{P_i} \vec{w}\, ds\ ;\quad \vec{\Omega}_i \wedge \vec{X}_i = \iiint_{P_i} \vec{w} \wedge \vec{x}\, ds\,. \tag{5}$$

where $\vec{w}$ is the absolute vorticity. So, we obtain the following discrete evolution equations for $\vec{X}_i, \vec{\Omega}_i$:

$$\begin{cases} \dfrac{D\vec{X}_i}{Dt} = \vec{U}_\infty + \vec{U}_w + \vec{U}_f + \vec{U}_{ext}\left(\vec{X}_i, t\right) \\ \dfrac{D\vec{\Omega}_i}{Dt} = -\dfrac{1}{4p} \displaystyle\sum_{p=1(\neq i)}^{N_j+N_p(t)} \Big(\frac{3}{\left|\vec{X}_p - \vec{X}_i\right|^5} \left(\vec{X}_p - \vec{X}_i\right)\left(\vec{\Omega}_i \cdot \left(\vec{\Omega}_p \wedge \left(\vec{X}_p - \vec{X}_i\right)\right)\right) \\ + \dfrac{1}{\left|\vec{X}_p - \vec{X}_i\right|^3} \left(\vec{\Omega}_p \wedge \vec{\Omega}_i\right)\Big) + \left(\vec{\Omega}_i \cdot \overline{\overline{grad}}\right)\left(\vec{U}_\infty + \vec{U}_{ext}\right)(\vec{X}_i, t) + n\Delta\vec{\Omega}_i \end{cases} \tag{6}$$

N_j, $N_p(t)$ and N_f are respectively the numbers of the bound vortex particles equivalent to the dipoles of the lifting surfaces, of the free vortex particles and of the panels. The following approximation formula has been used:

$$\vec{U}_w\left(\vec{X}_i, t\right) = -\frac{1}{4p} \sum_{p=1(\neq i)}^{N_p(t)} \frac{\vec{\Omega}_p(t) \wedge \left(\vec{X}_p - \vec{X}_i\right)}{\left|\vec{X}_p - \vec{X}_i\right|^3};$$

$$\vec{U}_f\left(\vec{X}_i, t\right) = -\frac{1}{4p} \sum_{p=1(\neq i)}^{N_f} m_p(t) \sum_{n=1}^{4} \vec{U}_{ip}^n,$$

$$\vec{U}_{ip}^{n} = \frac{\vec{r}_{ip}^{n_1} \wedge \vec{r}_{ip}^{n_2}}{\left|\vec{r}_{ip}^{n_1} \wedge \vec{r}_{ip}^{n_2}\right|^2}\left[\left|\vec{r}_{ip}^{n_1}\right| + \left|\vec{r}_{ip}^{n_2}\right|\right]\left[1 - \frac{\vec{r}_{ip}^{n_1} \cdot \vec{r}_{ip}^{n_2}}{\left|\vec{r}_{ip}^{n_1}\right|\left|\vec{r}_{ip}^{n_2}\right|}\right] \qquad (7)$$

The dipole distribution strength *m*, used to compute $\vec{U}_f$, is chosen in order to satisfy the body condition on the sail panels, leading to a linear matrix system:

$$[A][m] = [S] \qquad (8)$$

$[S]$ is the known vector of boundary conditions and $[A]$ the square influence matrix which is a function of the sail geometry, with the elementary coefficient:

$$a_{ij} = \frac{\vec{n}_i}{4p} \sum_{n=1}^{4} \vec{U}_{ij}^{n} \qquad \text{[cf eq. (7)]}$$

To avoid the singular behaviour of the previous equations when $\vec{X}_p$ tends to $\vec{X}_i$, a smoothing function is used. Hereafter, the singular kernel of eq. (7) has been replaced by the convolution product of this kernel by the function *f* defined by:

$$f(r) = r^3 / \left(1 + r^6\right)^{1/2}.$$

Consequently for the desingularised Biot-Savart law, we then obtained:

$$\vec{U}_w\left(\vec{X}_i, t\right) = -\frac{1}{4p} \sum_{p=1(p\neq i)}^{N_p(t)} f\left(\frac{\vec{X}_p - \vec{X}_i}{d_i}\right) \frac{\vec{\Omega}_p(t) \wedge \left(\vec{X}_p - \vec{X}_i\right)}{\left|\vec{X}_p - \vec{X}_i\right|^3} \qquad (9)$$
$$= -\frac{1}{4p} \sum_{p=1}^{N_p(t)} \frac{\vec{\Omega}_p(t) \wedge \left(\vec{X}_p - \vec{X}_i\right)}{\left(\left(\vec{X}_p - \vec{X}_i\right)^6 + d_i^6\right)^{\frac{1}{2}}}$$

where d_i is the distance with respect to the singularity, at which the regularisation is performed. The amount of vorticity initially contained in the particle is obtained by the Bernoulli equation along the separation line (with $\vec{U}_{te} = \frac{1}{2}\left(\vec{U}^{+} + \vec{U}^{-}\right)$, the trailing edge velocity):

$$\frac{\partial m}{\partial t} + \vec{U}_{te} \cdot \overrightarrow{grad} m = 0$$

During one step time dt, the location and the vorticity of the new vortex particle are obtained by the following equations:

$$\vec{\Omega}_i = \left[d\,l_i\left(m_i(t+\Delta t) - m_i(t)\right)\right]\vec{i} + \left[\Delta t\left|\vec{U}_{te}\right| \frac{m_{i+1} - m_{i-1}}{2}\right]\vec{j}; \qquad (10)$$
$$\vec{X}_i = \vec{X}_{te} + \vec{U}_{te}\frac{\Delta t}{2}$$

$\left(\vec{X}_{te}, \vec{i}, \vec{j}, \vec{n}_i\right)$ is the local frame of reference to panel i, $\vec{n}_i$ is the unit normal vector and $\vec{i}$, the tangent vector at the trailing edge. dl_i is the length of the part of the contour of panel *i* on the trailing edge. For more generality, two Cartesian frames of reference are used. The first one is fixed (inertial frame), and the second one moves relatively to the first one with the translation velocity $\vec{V}_0$ and the angular velocity $\vec{\Phi}$:

$$\vec{U}_e(M) = \vec{V}_0(O) + \vec{\Phi} \wedge \overrightarrow{OM}$$

The relative velocity $\vec{U}_r(M)$ in the moving frame can be deduced from the velocity $\vec{U}_a(M)$ of a fluid particle in the absolute frame of reference by:

$$\vec{U}_r(M) = \vec{U}_a(M) - \vec{U}_e(M),$$

leading to the following expression for the right hand side of equation eq. (8), due to the body condition:

$$S(t) = -\left(\overrightarrow{U_\infty}(t) + \overrightarrow{U_w}(t) + \overrightarrow{U_{ext}}(t) - \overrightarrow{U_e}(t)\right) \cdot \vec{n}$$

The link between the solid wall discretisation and the wake has been established through a vorticity transfer from the lifting surfaces to the wake. Taking into account the body motion $\vec{U}_e(M)$, we obtain:

$$\vec{\Omega}_{ia} = \left[d\,l_i\left(m_i(t+\Delta t) - m_i(t)\right)\right]\vec{i} + \left[\Delta t\left|\frac{\vec{U}_+ + \vec{U}_-}{2} - \vec{U}_e\right| \frac{m_{i+1} - m_{i-1}}{2}\right]\vec{j};$$
$$\vec{X}_{ir} = \vec{X}_{te} + \left(\vec{U}_e + \frac{\vec{U}_+ + \vec{U}_-}{2}\right)\frac{\Delta t}{2}$$

The absolute vorticity $\left(\vec{w} = \overrightarrow{rot}\vec{U}_a\right)$ on each particle has to satisfy the Helmholtz equation written in the moving relative frame:

$$\frac{D\vec{X}_r}{Dt} = \vec{U}_a - \vec{U}_e; \; \frac{D\vec{w}}{Dt} = -\left(\vec{w} \cdot \overline{\overline{grad}}\right)\vec{U}_a + \left(\vec{\Phi} \wedge \vec{w}\right) \qquad (11)$$

where $\frac{D}{Dt} = \frac{\partial}{\partial t} + \left(\vec{U}_r \cdot \overline{\overline{grad}}\right)$ is the convective derivative in the moving relative frame of reference.

For a better representation of the real flow around the sails, the following wind gradient has been used in the calculations:

$$U(z) = U_\infty(z_0 = 20m)(z / z_0)^{1/7} \text{ if } z < z_0;$$
$$U(z) = U_\infty(z_0) \text{ for } z \geq z_0$$

The version of the aerodynamic code used in the following paragraphs of the present study does not include the fluid-structure coupling which will be included later.

3.2 Sail grid for the First Class 8 hull

The rig is made of a fractional mast, a genoa and a main sail. The opening angle of the chord (defined as the line joining the tack point and the clew one) of the genoa with the boat axis is 12°. The luff length of the main sail is 10m, the one of the foot is 3.4m. The opening angle of the boom with the boat axis is 4°. The distribution of the volume, the twist angle, the roach and the whole set of characteristics of the sails have been given by the sail maker Bernard Mallaret (Delta Voile Company).

4. HYDRODYNAMIC-AERODYNAMIC COUPLING

4.1 Presentation of the method

To determine the speed and the attitude of the boat for given wind conditions, the hydrodynamic forces and moments around the hull and the aerodynamic forces and moments on the sails for the various values of the speed, of the yaw and heel angles are required. The coupling technique is the determination of the balanced sailing boat attitude in navigation upwind when the boat is submitted to the hydrodynamic forces (due to the hull) and the aerodynamic forces (due to the sails) in steady conditions (no waves). Aerodynamic forces and moments (subscript a) on the sails and hydrodynamic ones (subscript h) on the hull are defined on figure 3. The Oxyz frame of reference has Oz axis vertical and Ox axis in the plane of symmetry of the boat, directed into the direction of the boat motion; O is the ship centre of gravity. Ox'y'z' is fixed to the body and is derived from the previous one by a rotation of the heel angle j around the Ox axis.

It is also required to define the gravity forces on the boat. The total boat mass M_t=1835kg is applied at the center of gravity. It includes the keel mass M_k=600kg, applied at point G located at (0,0,z'=-1m) and the crew mass, M_c=391kg, located at point G'(0,y'=-1.2m,0). The system obtained writing the steady equilibrium conditions of the boat is quite complex, leading to six equations, so we have made some simplifying assumptions.

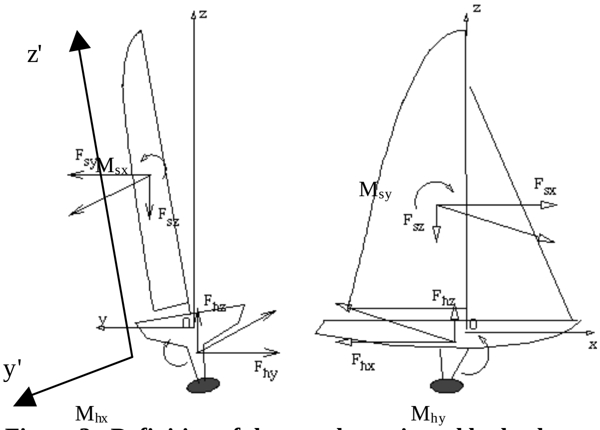


Figure 3 : Definition of the aerodynamic and hydrodynamic forces and moments on a sailing boat

The trim and sinkage of the boat have been neglected and also the variation of the submerged volume (and consequently of the hydrostatic vertical force). In the case of a well balanced boat, the forces induced by the rudder are weak. So, we assume furthermore than $M_{sz}=M_{hz}$. In a first step, we have not used the hydrodynamic moments obtained from the hydrodynamic calculations. The heel equilibrium is computed only from the static moments due to the various weights and the sail moments. Then, we have to solve the system of only 3 equations:

$$\begin{cases} F_{sx} = F_{hx};\ F_{sy} = F_{hy}; \\ M_{sx} + \overrightarrow{OG} \wedge (-M_k g\vec{z}) + \overrightarrow{OG'} \wedge (-M_c g\vec{z}) = 0 \end{cases} \qquad (12)$$

From these equations, it is possible to calculate estimations of the boat velocity and of the leeway and heel angles. The hydrodynamic forces are calculated by the code Poseidon described in a previous paragraph. From the forces and moments expressed as function of the 3 parameters (speed $0 \le U_\infty \le 6$m/s, leeway angle a from 0° to ±10° and heel angle j from 0° to ±15°), a continuous interpolation surface is built using an interpolation function (Spline bi-cubic function). So we can compute all the hydrodynamic forces and moments included in eq. (12), once these 3 parameters are known. These functions are included in the aerodynamic code (developed in [7]) where at each time step, the aerodynamic forces induced by the sails are estimated. The process is iterative and enables when the convergence is reached, to obtain the boat equilibrium attitude and its velocity (speed, drift and heel angles, apparent wind angle and speed). The method is based on the resolution of the following Newtonian system:

$$\begin{cases} M_t A_{bx} = F_{sx} - F_{hx}\ (a) \\ M_t A_{by} = F_{sy} - F_{hy}\ (b) \\ M_{sx} + \overrightarrow{OG} \wedge (-M_k g\vec{z}) + \overrightarrow{OG'} \wedge (-M_c g\vec{z}) = 0\ \ (c) \end{cases} \qquad (13)$$

where A_{bx} and A_{by} are the x and y components of the translation acceleration. By integration, the boat speed, the new apparent wind speed and the new apparent wind angle are estimated. About 150 to 250 iterations are required to obtain an equilibrium state ($A_{bx} \cong A_{by} \cong 0$).

Once the equilibrium state is reached, it is possible to calculate by integration the acceleration of the boat speed and also the boat attitude (drift and heel angles) using the Adam-Bashford integration scheme. For these equations, only sailing boat upwind can be considered, the angle of incidence is restricted to a value of 70° maximum from the true wind direction. There are two possibilities in the coupling. Equation (13c) is used to calculate either the variation of the crew mass located in G' with an a priori given heel angle; in this case, it is possible to impose a maximum value for the crew weight, the heel angle becoming free if this value is reached. The other possibility is to compute the heel angle, with a fixed crew weight in G'.

At the beginning of the calculation, during some few iterations, the boat is assumed to be without velocity and only the sails are in the wind, real wind being taken as the apparent one. This first step ended when the starting vortices on the sails are created and leave the sail trailing edges. Then the boat is assumed to move from rest but with a possible variation of the heel angle or of the crew mass. Finally at the last step, the boat can have a variation of the leeway angle. It had been observed that in this case, the beginning of this third step produces a sharp variation of the heel angle. This last step is finished when a steady equilibrium is reached. The computational time is about 2.5 to 4 h on a personal computer with 1,6Ghz processor.

4.2 Results of the coupling calculations

Figure 4 shows the variation of the apparent wind angle (AWA), and of the boat speed versus the time, calculated during the convergence of the calculations for a wind velocity of 7 knots with a direction of 44°; the chosen heel angle is j=4°. The starting of the hull is at the time t=1.75s and the time corresponding to a free leeway is t=4.25s. A good convergence is reached for those two quantities.

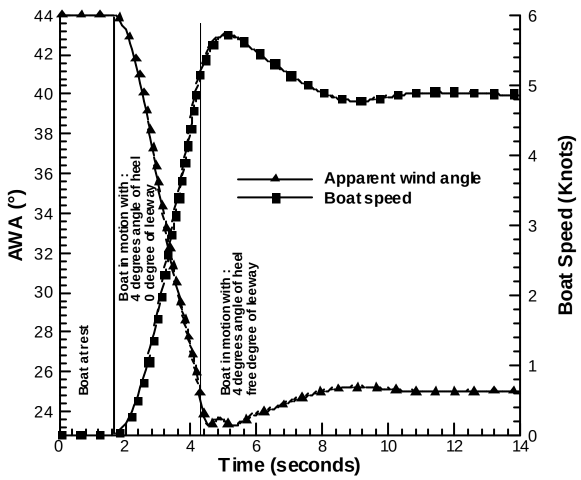


**Figure 4 : Apparent wind angle and boat speed versus time during the convergence of the calculations
Wind speed 7 knots**

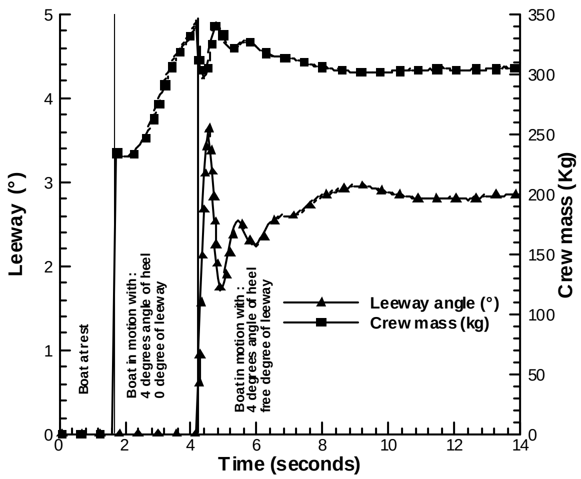


**Figure 5 : Leeway angle and crew mass versus time during the convergence of the calculations
Wind speed 7 knots**

Figure 5 is a similar graph but for the leeway angle and the crew mass located in *G'*. The convergence is also quite fair and is reached after about 12s. It can be observed that when the leeway angle becomes free, sharp variation of the crew mass occurs.

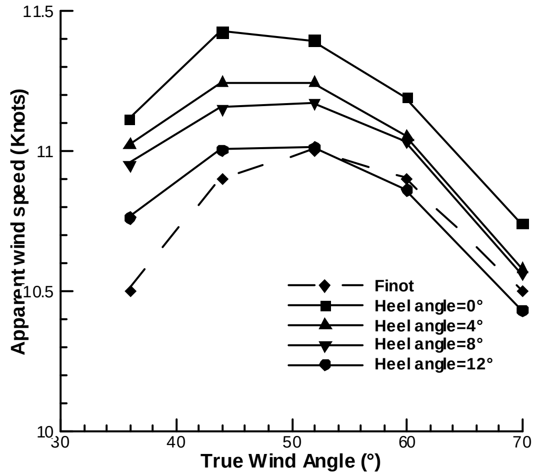


**Figure 6: Apparent wind speed versus the true wind angle for various values of the heel angle
Wind speed 7 knots**

The values of the apparent wind speed versus the true wind angle (TWA in °) are plotted in figure 6 for the heel angle ranging from 0° to 12°. All the curves have similar shapes, increasing first with TWA, with a maximum between 44° and 52° and then decreasing; the apparent wind speed decreases when the heel angle increases. It can be noticed that for high values of the apparent wind angle, the sail shape is probably no more correct and, that in this case, a fluid-structure coupling taking into account the elasticity of the sails will probably improve the results. Results obtained for j=12° are very close to the values computed by the empirical VPP of the naval architect Finot, particularly for TWA>50°.

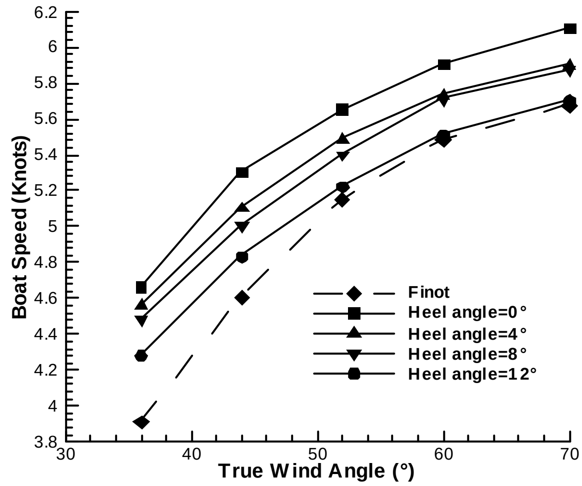


**Figure 7: Boat speed versus the true wind angle for various values of the heel angle
Wind speed 7 knots**

Figure 7 is a similar graph to figure 6, but is presented as a function of the boat speed V_b (in knots). V_b increases with the TWA but decreases with the heel angle at fixed TWA. Nevertheless, it must be remembered that in these calculations, the sails are considered in these calculations as rigid, so the boat speed must be in some cases overestimated. Here also, results for $j = 12°$ are close to those of Finot, particularly at larger values of TWA.

5. CONCLUSIONS

The first result obtained by the coupling of aerodynamic computations of the flow around sails and hydrodynamic calculations of the steady flow around a ship hull with lifting effects has been achieved. It had been applied as example to a sailing boat with a First class 8 hull and a fractional mast, a genoa and a main sail. This tool, after validation and improvement, will be possibly used to calculate the performance of a sailing boat even at the design stage.
The aerodynamic code is based on a lifting surface method for the sails and a vortex element method for the wakes. The hydrodynamic one is a potential based panel method using the wave resistance Green function, with a linear version of the Kutta-Joukowsky condition. The main feature of this method is to perform, with a great accuracy, the boundary integrations by interchanging the boundary and Fourier integrations, the first being performed analytically and the latter by an Adaptative Simpson method of integration (with an integration step decreasing when the oscillations of the integrand increases). The attitude of the sailing boat at equilibrium is computed by solving the longitudinal and transverse force equations and by a crude equation concerning the heel angle of the boat (either the boat is at free heel angle with a fixed crew or the weight of the crew located outside of the boat can vary, with a fixed heel angle a priori chosen or still with a version where the crew mass has a maximum and then the heel angle becomes free). In spite of the difficulty to have results enabling the validation of the presented results, they seem to be of good quality when compared with those of an empirical VPP available.

The next steps to improve the quality of the method presented here are to take into account all the hydrodynamic forces and moments in the coupling method, particularly for the calculation of the heel equilibrium. The fact of taking into account other equations, particularly for the translation in z giving the sinkage and the pitch equilibrium for the trim angle will be more difficult to perform because of a needed regridding of the hull due to its change with sinkage and trim and heel angles for the hydrodynamic calculations. The aerodynamic problem and the structure one are obviously coupled, so that an interaction model has to be used, simply approximated as a non homogeneous anisotropic membrane problem. Unfortunately, this problem does not necessarily have a unique solution. This yields a mathematical problem which cannot be solved by means of standard tools. So, for the sail computations, an improvement will be to use another existing version of the aerodynamic code employed, taking into account a fluid-structure coupling. It uses finite elements for the elastic problem, with an iterative process through the aerodynamic load and the sail deformations. Finally as the full aerodynamic code is unsteady (time domain) and that it exists an unsteady version (frequency domain) of the hydrodynamic code, waves can be taken into account, at least the added resistance, in a further development.

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