NUMERICAL SIMULATION OF A NAVIGATING SAILING BOAT

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1.Introduction

The progress of numerical codes to compute both the aerodynamic of sails and the steady hydrodynamic flow about hulls enable today to develop a numerical tool to be used in the design of sailing boats. We present recent results concerning the numerical simulation of a navigating sailing boat. This simulation is done by the coupling of aerodynamic and of hydrodynamic computer codes. The hydrodynamic computations are based on a velocity based first order panel method using either the wave resistance or the diffraction-radiation with forward speed in the frequency domain Green function. The unsteady aerodynamic simulation is based on a description of the flow by means of lifting surfaces for the sails and of a particle method for its wake. At each time step, particles are created along given lines (the trailing edge of the sail) in order to satisfy a condition formally derived from the Joukowsky condition. The velocity field of the particles is computed by the Biot-Savart relation and the deformation term is obtained through an integral relation by differentiating the Biot-Savart law.

We consider the motion of a boat sailing upwind (incidence from the true wind direction α<70°) to keep the flow attached on the sail. At each time step, forces on the sails are computed and from the knowledge of the hull's position the forces on the hull are obtained. The acceleration is estimated by the solution of the New-ton's equation. The velocity and the position of the boat are estimated from the acceleration by the Adam Bash-forth integration scheme. Examples of results obtained for a First class 8 sailing boat in steady flow are presented.

2. Numerical methods

2.1 Hydrodynamic flow

The flow around a ship advancing in waves or in a quiet ocean along a straight path with constant velocity U in water of effectively infinite depth and lateral extent is considered. Based on the assumptions of perfect fluid, irrotational flow and small wave steepness, the velocity potential can be written as the sum of a basic (steady) and a time harmonic unsteady potentials. Either the steady velocity potential or the spatial part of the unsteady one must satisfies the Laplace equation into the fluid, the body condition on the body S, the linearised free-surface boundary condition on the mean free-surface S_F (z=0), plus the radiation condition and the condition at infinity. ω is the encounter frequency.

By use of the Green's third identity for a computational closed domain limited by the body surface S, the free surface S_F and the surface of a half sphere located at infinity S_∞, the steady ot the spatial component of the velocity potential ϕ can be written under the form of an integral equation involving the corresponding Green function satisfying the same conditions than the potential, except the body one. With the previous assumptions and by transforming the boundary integral on the free surface into a contour one on the waterline C_L using the Stokes theorem the potentials are given by for:

$$C(x,y,z)\phi(x,y,z) = \iint_S \left(G\frac{\partial \phi}{\partial n} - \phi\frac{\partial G}{\partial n}\right)ds - F\int_{C_L}\left[2i\tilde{\omega}\ \phi G + F\left(G\ \frac{\partial \phi}{\partial x'} - \phi\frac{\partial G}{\partial x'}\right)\right]dy' \qquad (1)$$

where $\tilde{\omega} = \omega\sqrt{L/g}$ is the non dimensional circular frequency and $F = U/\sqrt{gL}$, the Froude number. A mixed distribution of sources and doublets is used By applying the $\partial/\partial n$ operator to the previous equation, an integral equation enabling to compute the unknown distribution can be obtained using the body condition Then, potential, pressure forces and wave elevation can be calculated.

For the numerical resolution, the hull surface is divided into n_c columns of n_p panels giving $n_c \cdot n_p$ panels on the whole body and the wake is divided into n_c semi infinite strips. The integrations on elementary panel or waterline segment over Green functions or derivatives are computed after interchanging the space and Fourier integrations. The first ones are computed analytically following [1]. The Fourier integration, using a single integral formula involving the complex exponential integral function, are calculated in the θ-space as in. [2] by an adaptive quadrature method (where the integration step decreases as the integrand becomes more oscillating). Detail can be found in [3,4].

2.2 Aerodynamic of the sails

Flow modelling is based on the vortex element method (VEM). This method is suitable for external flows for bounded vorticity support. It is the case for lifting surfaces, where the turbulent shear flow along the surface and the wake formed by the vortex shedding along the trailing edge are represented by dipole surface distribution and vortex sheets, respectively. During the last ten years, this method was successfully validated, particularly to capture dynamic wake effects in details.

This method is basically made of two parts : a lifting body problem and a wake problem. These two problems are coupled by means of a kind of Kutta condition which has been derived from the kinematic and dynamic conditions along the separation lines. Usually, these lines are reduced to the trailing edges although more complicated situations have sometimes been considered. Except when writing this Kutta condition, the flow has been assumed to be inviscid. The lifting problem is solved by means of a boundary integral method : the surface of the body is represented using panels of rectangular shape which are used to satisfy the potential slip conditions. Specifically, a dipole strength was associated with each panel, and the strength of the dipole was adjusted by imposing that the normal velocity component at the surface of the body must vanish at control points. The wake has been modeled by means of the particle method itself, [5]. According to this method, the vorticity distribution within the wake is described by means of particles carrying vortices. The motion of particles is computed in a Lagragian framework. The vorticity on each particle has to satisfy the Helmholtz equation. The details of these calculations are presented in [6], [7].

2.3 Coupling method

The coupling technique is the determination of the balance sailing boat position in navigation up the wind when it is submitted to the hydrodynamic forces (due to the hull) and the aerodynamic forces (due to the sails).

2.3.1. Forces and moments on a sailing boat

The forces acting on the boat are the aerodynamic forces $\vec{F}_s$ on the sails creating the moment $\vec{M}_s$ (with components M_{st} responsible of the trim angle, due to F_{sx} and F_{sz}, M_{sh} for the heel angle, due to F_{sy} and F_{sz} and M_{sy} for the yaw angle, due to F_{sx} and F_{sy} and the hydrodynamic forces on the hull $\vec{F}_h$, creating the moment $\vec{M}_h$. The balance of forces requires the following conditions:

$$\vec{F}_s = \vec{F}_h ; \vec{M}_s = \vec{M}_h$$

To solve this system, some simplifications have to be done:

- The vertical components of forces are opposite (small variation of the submerged volume of the hull, $F_{sz}=F_{hz}$);
- For a well-balanced boat, the forces induced by the rudder are weak and so, the moment producing the turning of the boat too, so $M_{sy}=M_{hy}$.
- Moment M_{st} responsible of the trim modification can be balanced by an hydrodynamic force on the hull or by the displacement of a member of the crew, so $M_t=M_{ht}$;
- Finally in this simulation, we neglect that the heel angle, so $M_h \cong M_{hh} \cong 0$.

Then, we have to solve the system:

$$F_{sx} = F_{hx} ; \; F_{sy} = F_{hy}$$

These 2 equations enable to obtain an estimation of the boat speed and drift angle. Hydrodynamic forces are calculated by the hydrodynamic code, section 2.1. From the numerical forces expressed in function of velocity and drift angle, a continuous interpolation surface is build by using an interpolation function. We then determine the hydrodynamic forces from the knowledge of the boat speed and drift angle. This function are included in the aerodynamic code 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 an equilibrium point of the boat (speed, drift angle, apparent wind angle and wind speed).

2.3.2 Description of the coupling method

The method is based on the resolution of the following Newton's system:

$$MA_{bx} = F_{sx} - F_{hx} \;(a); \; MA_{by} = F_{sy} - F_{hy} \;(b) \qquad (2)$$

where A_{bx} and A_{by} are the x and y-component of the acceleration and M is the boat mass in navigation (with crew and equipment). By integration, the boat speed, the new apparent wind speed and wind angle are estimated. About 50 iterations are required to obtain an equilibrium state ($A_{bx} \cong A_{by} \cong 0$). Then after obtaining the equilibrium position, the speed and drift angle of the boat are calculated. Initially, the boat is assumed to be at rest and the sail in an uniform flow. After some few iterations, time required for the formation of the starting vortex and its departure from the sail trailing edge, the boat is able to move without drift angle. The Newton equation in direction x is then solved eq.(2a)

3. Results of the coupling method

3.1 Description of the case under study

The first Class is a 8m long ship. This boat has been designed by the architects Jean-Marie Finot and Jacques Fauroux. We will present here the hull and the sails of this sailing boat. The hull is composed of 960 panels; the water plane length is 6.65m and the maximum draft is 1.92m. 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 repartition 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). The numerical grid is 10*5 panels for the genoa and 10*8 panels for the main sail.

3.2 Hydrodynamic results on hull

The total resistance for a Beneteau First Class 8 without heel angle has been calculated. The present results are in good agreement with tests measurements performed in the towing tank [8]. Here the friction resistance have been computed using the ITTC 57 formula. For tests, the model is at scale1/2.7 of the real hull with a length L=2.5m, but results correspond to the real size. As the Froude number increases, the calculations show some oscillations not observed on the measurements but classical in wave resistance. These results show the accuracy of the method. Table 1 shows the side force (also in newtons) for the hull with a null values of trim and heel angles for two values of the velocity at a yaw angle of –4°. Two different measurements are compared with the results of calculations showing also the accuracy of the method and its ability to predict the flow.

Trim angle(°)	Heel angle (°)	Yaw angle (°)	Froude numb. F	C_y Test	C_y Calculations
0	0	-4	0.35	0.0295	0.02838
0	0	-4	0.5	0.0325	0.02793

Table 1 Side force for the yawed First Class8 hull

Figure 1 shows the graph of the lift and drag areas used to interpolate the drag and lift versus the yaw angle and the boat speed for the coupling calculations. We observe a linear behavior of the lift with the drift angle.

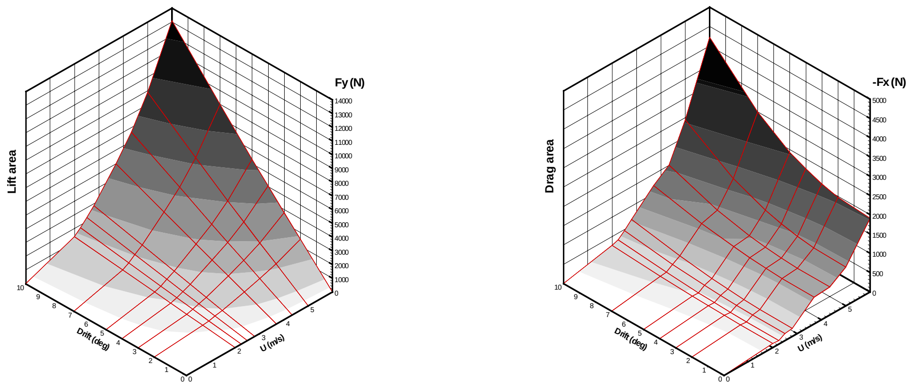
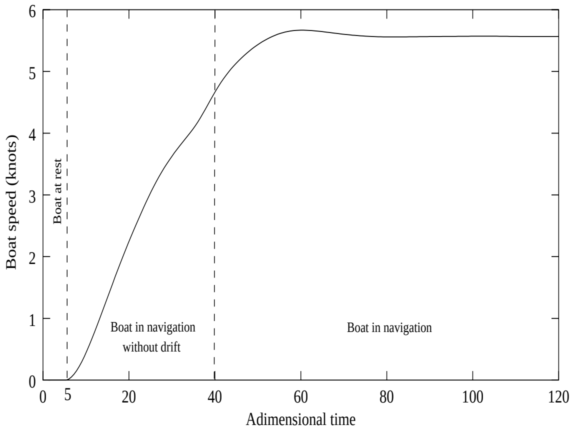


Figure 1 Lift and drag surfaces used in the coupling calculations

3.3 Result of the coupling method

Figure 2 plots the variation with non dimensional time $\tilde{t}$ of the boat speed for a true wind speed of 7 knots and a true wind angle of 44°. At the beginning, $\tilde{t} < 5$, the boat is at rest. For $5 < \tilde{t} < 40$, the boat is navigating without drift angle and for $\tilde{t} > 40$, the drift is included. For $\tilde{t} > 60$, an equilibrium state is reached. On figure 3, we compare velocity performance prediction (VPP) obtained by the present method with values obtained by an empirical method performed by the naval architect Finot. The graph plots the boat speed (in knots) versus the true wind angle. The two curves are nearly parallel but our method leads to higher values of the boat speed. Two explanations can be done to this: first, in our calculations, we an have considered an hydrostatic equilibrium without crew team, leading to an underprediction of the submerged volume of the hull and consequently an overprediction of the boat speed; secondly, we calculate only an inviscid (induced) aerodynamic drag of the sails, leading to a weaker drag that the real one and leading also to an overprediction of the velocity. Nevertheless, no experimental results for a VPP have been obtained and it is necessary to validate both kind of results (empirical calculation or present method) with experimental data.



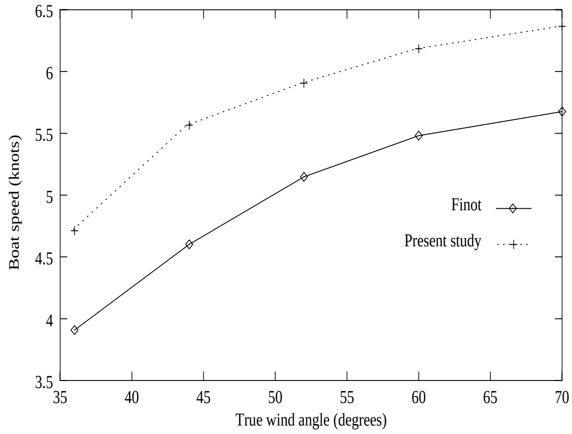


Figure 2 Boat speed evolution with non dimensional time Figure 3 Comparison of VPP for the boat speed

4. Conclusion

We have presented the first results obtained by the coupling of an aerodynamic computing code with an hydrodynamic one in order to predict the performances of a sailing boat, even at the design stage. The aerodynamic code is based on a lifting surface model for the sails and a particle method for the wake (Vortex Element Method). The hydrodynamic calculations are performed by a Boundary Element Method with a Green function satisfying a linearized free surface boundary condition; a great care of the accuracy of the surface and of line integrals over the Green function or over its derivatives has been taken. The equilibrium of the sailing boat is obtained by solving a simplified set of two Newton equations (x and y force components) enabling to compute the boat speed and drift angle by an iterative process. The forces calculated from the hydrodynamic code are included it aerodynamic one under the form of interpolation from discrete values. The results presented, restricted to steady flows, have been shown to be of good quality compared with the VPP codes generally used, so that the method can be used as a VPP code during the design stages of a sailing boats. The next stages of this work is to extend the validity of the method to heeled hulls and to the calculation of the deformations of the sails and of the viscous drag. The ability of optimizing how to trim the sails will be also an improvement of the method. The following stages will be to deal with unsteady conditions to predict the performance of the sailing boat in regular waves coupling the frequency domain hydrodynamic method of computation with a time domain unsteady version of the calculation of the flow on the sails. It will be also necessary to validate the method and experimental data would be of great interest for this problem.

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