CONCEPTION DE LA COQUE D'UNE VEHICULE EN CONDITION DU SNORKEL AVEC UNE APPROCHE DE L'HYDRODYNAMIQUE NUMERIQUE

HULL SHAPE DESIGN OF A SNORKELING VEHICLE USING NUMERICAL HYDRODYNAMICS

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Résumé

Un logiciel en MATLAB pour le problème de résistance de vagues avec condition de surface libre non linéaire est utilisé en combinaison avec des estimations empirique pour la résistance visqueuse dans une approche d'optimisation formelle en visant d'améliorer un prototype existant d'un AUV. L'amélioration est confirmée par des essais dans un bassin d'essais des carènes.

Summary

A wave resistance code with nonlinear free-surface condition implemented in MATLAB is used with empirical estimates for viscous resistance in a formal optimization approach aimed to improve an existing prototype for an AUV. The improvement is confirmed by model tests.

I. INTRODUCTION

Autonomous underwater vehicles (AUVs) and autonomous surface vehicles (ASVs) are increasingly used in offshore, oceanographic and navy applications. The autonomy of these vehicles is frequently limited by power requirements. *Bertram and Alvarez (2006)* discussed general guidelines for hull design of such vehicles, showing that designs following torpedo or submarine shapes are suboptimal.

The 'Cormoran', Figure 1, is a simple low-cost coastal water observing platform, a hybrid between AUV and ASV. It moves at the sea surface and dives to make vertical profiles of the water column following an established plan, Figure 2. The vehicle is immersed by flooding an internal reservoir with seawater. Conversely, a piston pumps the seawater back from the internal reservoir to the sea to emerge. Gathered data is transmitted in real time to the laboratory. The prototype has a torpedo shape with a total length of 1.5 m, a diameter of 16 cm, and a displacement of 25 kg. The speed of 1±0.1 m/s results in a Froude number of F_n=0.26±0.025. Most of the time, the Cormoran will operate in snorkeling condition. The main body is then close enough to the water surface to make waves, and the mast pierces the water surface creating its own small wave system.

Figure 1. 'Cormoran' at IMEDEA

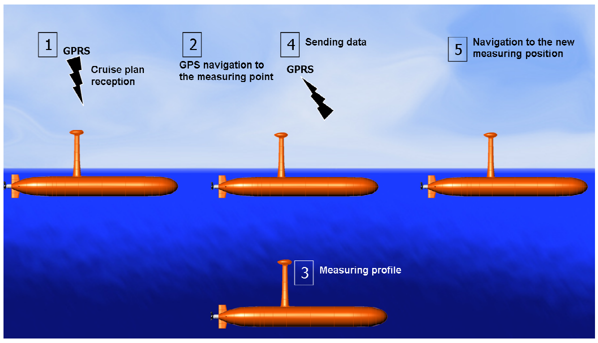


Figure 2. Cormoran working procedure

II. RESISTANCE COMPUTATION

The wave resistance in snorkeling and surfaced condition can be determined using advanced wave resistance codes, *Bertram (2000)*. These codes neglect viscosity and the action of the propeller, but determine iteratively the position of the free surface and the dynamic sinkage and trim. For a submerged body in snorkeling condition, the hydrostatic restoring forces are negligibly small. We assume that the automatic controller of the AUV will keep the AUV on an even keel and at constant water depth. We then have a simplified physical model as described in the following.

We consider a body moving with constant speed V in water of infinite depth, submerged at constant depth near the free surface of the water. The following simplifications are assumed:

- Water is incompressible, irrotational, and inviscid.
- Surface tension is negligible.
- There are no breaking waves.
- The hull has no knuckles which cross streamlines.
- Appendages and propellers are not included in the model.

The equations are formulated here in a right-handed Cartesian coordinate system with x pointing forward towards the bow and z pointing upward. The moment about the y-axis is positive clockwise. For more details on deriving the conditions and the numerical techniques, see *Bertram (2000)*. For the considered ideal flow, continuity gives Laplace's equation which holds in the whole fluid domain. A unique description of the problem requires further conditions on all boundaries of the fluid:

(1) Hull condition:	Water does not penetrate the ship's surface.
(2) Kinematic condition:	Water does not penetrate the water surface.
(3) Dynamic condition:	There is atmospheric pressure at the water surface.
(4) Radiation condition:	Waves created by the ship do not propagate ahead.
(5) Decay condition:	The flow is undisturbed far away from the ship.
(6) Open-boundary condition:	Waves generated by the ship pass unreflected any artificial boundary of the computational domain.

For the assumed ideal fluid, there exists a velocity potential ϕ such that $\boldsymbol{v} = \nabla\phi$. $\boldsymbol{v}$ indicates the velocity vector. The velocity potential ϕ fulfils Laplace's equation in the whole fluid domain:

$$\phi_{xx}+\phi_{yy}+\phi_{zz} = 0 \tag{1}$$

A coordinate x,y,z as index indicates here a partial derivative with respect to that coordinate.

The hull condition requires that the normal velocity on the hull vanishes:

$$\boldsymbol{n}\cdot\nabla\phi = 0 \tag{2}$$

$\boldsymbol{n}$ is the inward unit normal vector on the ship hull.

The kinematic free-surface condition gives at the water surface $z=\zeta$:

$$\nabla\phi\cdot\nabla\zeta = \phi_z \tag{3}$$

For simplification, we write $\zeta(x,y,z)$ with $\zeta_z = 0$.

The dynamic condition (atmospheric pressure at water surface) gives at $z=\zeta$:

$$\tfrac{1}{2}(\nabla\phi)^2 + gz = \tfrac{1}{2}V^2 \tag{4}$$

The problem features two special problems requiring an iterative solution approach: (a) A nonlinear boundary condition appears on the free surface, due to the dynamic boundary condition. (b) The free surface position is not a priori known. We approximate the potential ϕ by an arbitrary approximation Φ, and the free surface ζ by an arbitrary approximation Z. Combining the dynamic and kinematic boundary conditions and linearizing consistently around the approximations yields at $z=Z$, *Jensen et al. (1986), Bertram (2000)*:

$$\begin{gathered}2(\boldsymbol{a}\cdot\nabla\phi + \Phi_x\Phi_y\phi_{xy} + \Phi_x\Phi_z\phi_{xz} + \Phi_y\Phi_z\phi_{yz}) + \Phi_x^2\phi_{xx} + \Phi_y^2\phi_{yy} + \Phi_z^2\phi_{zz} \\ +g\,\phi_z - B\,\nabla\Phi\,\nabla\phi = 2\,\boldsymbol{a}\cdot\nabla\Phi - B(\tfrac{1}{2}((\nabla\Phi)^2+V^2) - g\,Z)\end{gathered} \tag{5}$$

with vertical particle acceleration $\boldsymbol{a} = \tfrac{1}{2}\nabla((\nabla\Phi)^2)$ and $B = (\boldsymbol{a}\cdot\nabla\Phi + g\,\Phi_z)_z/(g+a_3)$. The index 3 indicates the third component of the vector. This condition is rather complicated involving up to third derivatives of the potential, but it can be simply repeated in an iterative process which is started with uniform flow ($\Phi = \{-Vx,0,0\}$) and no waves ($Z=0$). In each iterative step, wave elevation and potential are updated yielding successively better approximations for the solution of the nonlinear problem. Convergence is usually rapid. Typically 3 or 4 iterations suffice. Once a potential has been determined, the forces can be determined by direct pressure integration on the hull:

$$\begin{gathered}f_1 = \int_S p\,n_1\,dS \\ f_3 = \int_S p\,n_3\,dS \\ f_5 = \int_S p\,(z\,n_1 - x\,n_3)\,dS\end{gathered} \tag{6}$$

S is the wetted surface. p is the pressure determined from Bernoulli's equation:

$$p = \tfrac{1}{2}\rho\,(V^2-(\nabla\phi)^2) \tag{7}$$

ρ is the density of water. The force in *x*-direction, f_1, is the negative wave resistance. The nondimensional wave resistance coefficient is:

$$C_W = - f_1/(½\, \rho\, V^2\, S) \tag{8}$$

The problem is solved using classical first-order Rankine panels as proposed by *Hess and Smith (1962,1964)* for the body. Desingularized Rankine point sources are used above the free surface. The desingularization distance is twice the grid spacing in x-direction. This distance was found to give more reasonable results than the dimensionally inconsistent recommendation of *Beck et al. (1999).* During the iteration, the collocation points at the free surface are updated, but the position of the sources remains unchanged. Mirror images of panels are used in y direction with respect to $y=0$. The decay condition - like the Laplace equation - is automatically fulfilled by all elements. The radiation condition and the open-boundary condition are fulfilled by adding an extra row of source elements at the downstream end of the computational domain and an extra row of collocation points at the upstream end, *Jensen et al. (1986), Thiart and Bertram (1998).* For equidistant grids this can also be interpreted as shifting or staggering the grid of collocation points vs. the grid of source elements. This technique shows absolutely no numerical damping or distortion of the wave length, but requires all derivatives in the formulation to be evaluated numerically.

The numerical model was implemented in Matlab, *Alvarez and Bertram (2007).* The advantage of Matlab is an easy visualization without need of external software. At a later stage, the method shall be transposed into Fortran for computational efficiency. The computational time on a Pentium IV processor machine of 3.06 GHz is typically 40 s for a grid of 1000 elements (unknowns).

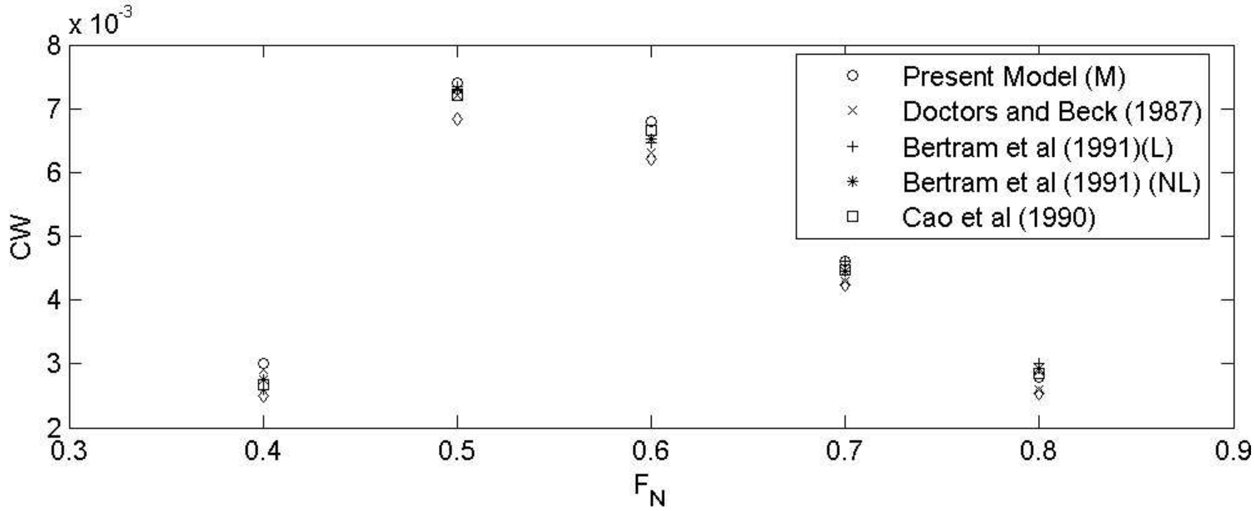


Figure 3. Wave resistance coefficient computed for the spheroid

III. MODEL VALIDATION

The wave resistance of an elongated spheroid with aspect ratio 1:5 and draft T=0.245·L, where L is the length of the spheroid, was used as a test case. For this spheroid, results can be compare with experiments and previous computations based on two different Rankine panel methods, *Bertram et al. (1991).* The numerical model has been implemented discretizing the body with 1127 panels on one half of the hull and a cosine law partition. The free surface was discretized with 1037 panels. Figure 3 compares the non-linear results for wave drag with results published by *Bertram et al. (1991).* The agreement is very good showing that the method was correctly implemented.

IV. OPTIMIZATION APPROACH

We neglect for the time being the snorkel, assuming no interaction between the wave systems of main body and the snorkel. This assumption may be justified, as the Froude numbers for main body and snorkel are different by two orders of magnitude. The length of the body is 1.5 m, the length of the snorkel in the waterline is 0.02 m.

We split the body in three simple segments of respective lengths L_a, L_c, L_f, for aft, center, and front part, Figure 4. The aft part and the front part follow from:

$$\mathrm{r_a} = R\left(1-\left(\frac{(L_a - x)}{L_a}\right)^{n_a}\right) \qquad \mathrm{r_f} = R\left(1-\left(\frac{(x - L_a - L_c)}{L_f}\right)^{n_f}\right)^{\frac{1}{n_f}}$$

r_b is the radius at the position x and R is the radius of the central cylinder.

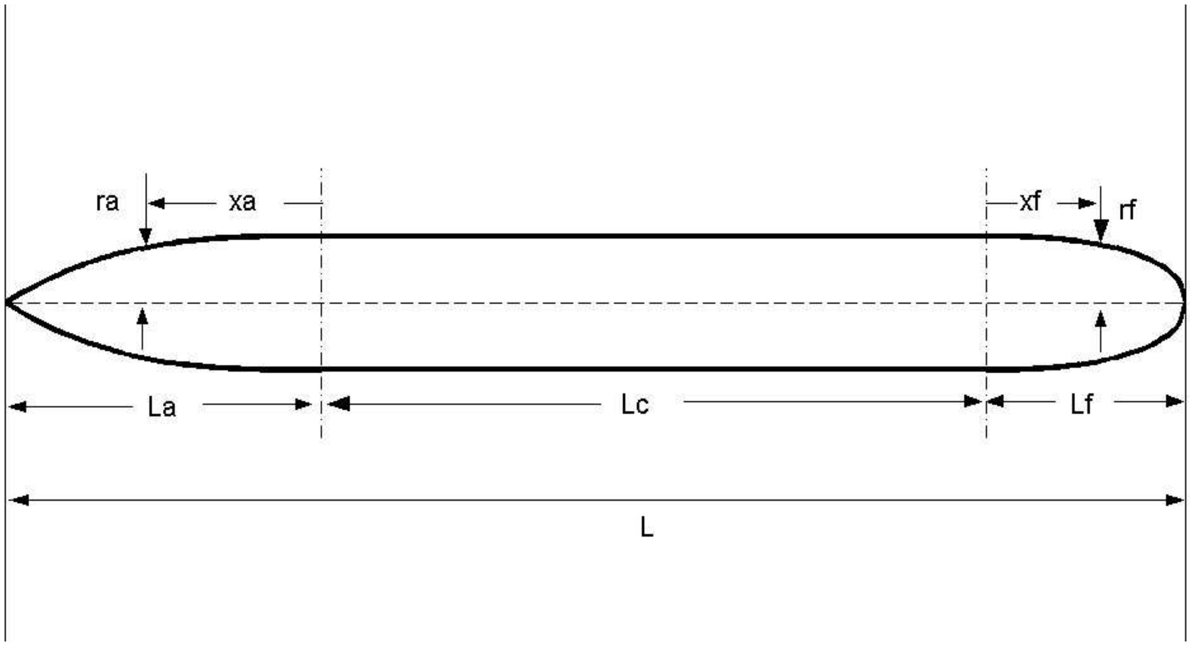


Figure 4. Geometry for optimization

The body was optimized for minimum total resistance averaged for 0.9, 1, and 1.1 design speed. The total resistance is computed as sum of wave resistance near the free, and the frictional resistance following ITTC'57. Wave resistance was computed with the Matlab wave resistance code described above. A total of 843 source elements were distributed on the body hull (343) and free surface (520), employing symmetry in *y* by mirror images of the elements, Figure 5.

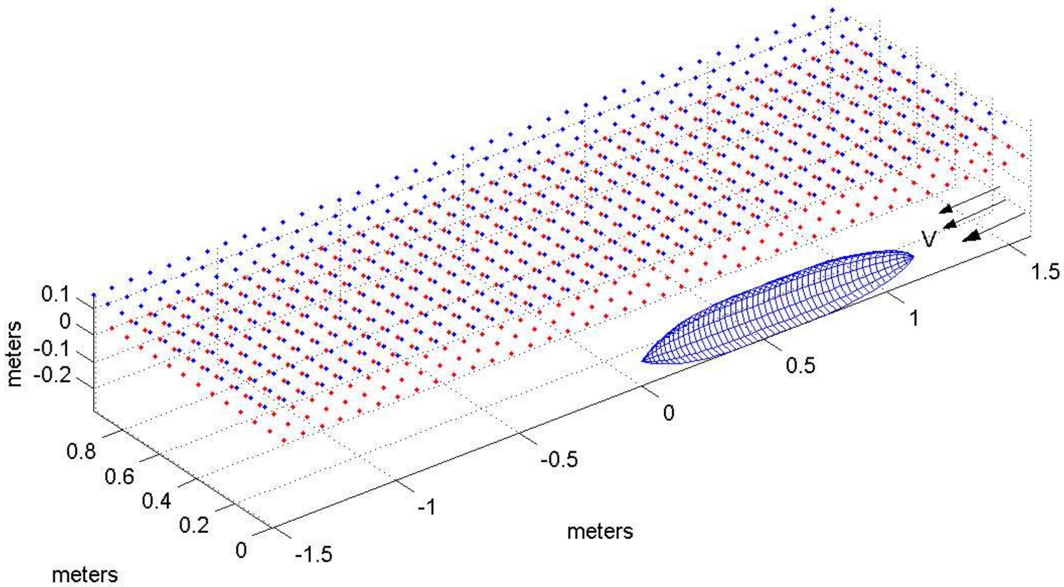


Figure 5: Grid for wave resistance computation

Constraints for the optimization were constant displacement volume and maximum length of the vehicle of 1.5 m. The stern angle of the aftbody was limited to a maximum value of θ=25°. Model test experience indicates that for the body in unpropelled condition, a stern cone angle of θ=20° can be regarded as a limit for flow separation for a parabolic outline of the aftbody, *Bertram and Alvarez (2006).* For the submarine in propelled condition, the flow acceleration due to the propeller prevents separation for much higher cone angles. A thicker aftbody is desirable for various reasons (internal arrangement, maneuverability, decreased frictional resistance due to smaller wetted surface).

We used a simulated annealing optimization algorithm which proved to yield better results than the standard sequential quadratic programming optimization routine of Matlab version 7. Comparative calculations revealed that the objective function has shallow and slightly oscillating contour lines making heuristic optimization algorithms more suitable than gradient based algorithms.

V. RESULTS

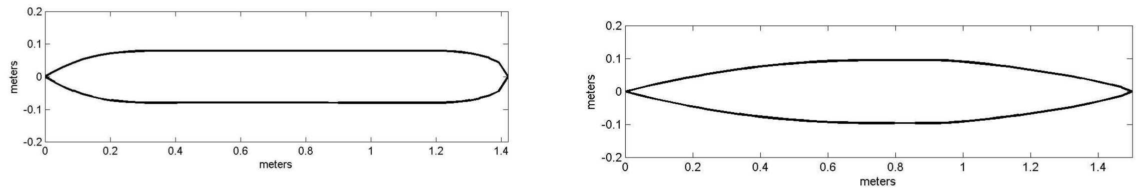
Bertram and Alvarez (2006) describe extensive preliminary studies of the optimization, which investigated:

- the influence of different computational models including a simple Michell integral approach which was found to be insufficient.
- the influence of various constraints
- influence of numerical grid resolution

The optimization required a total of 808 evaluations of the cost function leading to a total computation time of 15 hours. Table I and Figure 6 summarize the results. The optimized hull shape is shorter, with a much shorter parallel midbody and larger diameter, which also improves propulsion as a larger propeller diameter can be chosen. The power requirements then are effectively reduced by approximately 20%. The next applications released n_a and n_f to allow more arbitrary shapes. The tendency is to eliminate a parallel midbody completely which is feasible for a very small platform like the Cormoran, that does not require flat docking facilities.

Table I: Results of 'optimization'

	original	'optimized'
n_a	3	2
n_f	2.3	1.3
Total length	1.42	1.49
Length of aft part	0.38	0.73
Length of forward part	0.24	0.54
Radius	0.08	0.095
Total resistance	2.14 N	1.54 N



Original 'Optimized'

Figure 6. Geometries in optimization

The original prototype hull and the final optimized hull were tested in the ship model basin of the University of Trieste in Italy, Figure7. Preliminary results indicate that the optimized hull generates less wave resistance than the original shape for the range of speed considered. Conversely, the original shape is more efficient at speeds higher than 1.5 m/s.

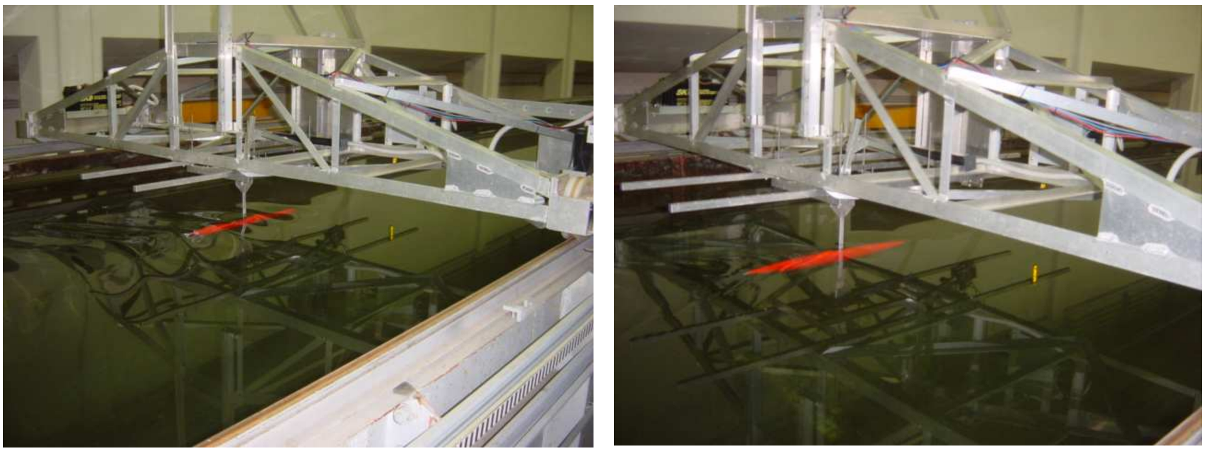


Figure 7. Original (left) and optimized (right) hull in model tests

VI. CONCLUSION

The presented work is in progress. The optimization model could be extended including further important hydrodynamic aspects, but these would require significantly more expense. The most important hydrodynamic aspects in our view are:

- Optimization of the propeller, including an investigation of the effect of nozzles.
- Consideration of the induced resistance in maneuvering, both for the control foils and the hull
- Consideration of the effect of seakeeping (in snorkeling condition)
- Consideration of viscosity in the model; probably least important as flow separation is unlikely based on empirical knowledge for submarine model testing and the surface friction is considered by a simple ITTC'57 formula.

Despite the limitations of the optimization model, the application indicates that underwater drones can be improved by using relatively classical hydrodynamics with a computational effort that allows incorporation in formal optimization even in the design stage.

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