Proceedings of 6th Transport Research Arena, April 18-21, 2016, Warsaw, Poland

Hydrodynamic characterization of USV vessels with innovative SWATH configuration for coastal monitoring and low environmental impact

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Abstract

The high costs associated with the use of research oceanographic vessels and the maturity of the unmanned surface vehicles (USV) makes now possible to develop systems for monitoring coastal areas based on networks of independent USVs. This type of vessels is a valid alternative to conventional vessels, which have a limited mission profile due to their high environmental impact (conventional propulsion systems based on polluting fossil fuels) inhibiting their access to protected coastal regions. Moreover, conventional vessels have high hydrodynamic resistance (limiting the autonomy) producing high levels of noise that can dramatically influence the monitoring equipment shipped: beside the environmental impact reduction, there is also the necessity of low-resistance/low-noise hydrodynamic specification. Consequently, the coastal monitoring (of also protected regions) needs unconventional vessels able to address both the issues related to the environmental impact and the hydrodynamic performance.

In this framework, this work aims to characterize the hydrodynamic performance of a system based on USV units able to launch and recover autonomous vehicles of different nature (gliders, AUVs, motor-gliders, wire-guided ROVs), and able to acquire environmental data (in the column water from free-surface to the sea floor), in order to meet the requirements of civil and military applications. The cutting-edge aspects that characterize the USV studied are the hull SWATH type (Small Waterplane Area Twin Hulls) non-conventional, optimized so as to ensure a unique seakeeping and a reduced resistance, along with the propulsion system with propellers in mantle, developed to combine propulsive efficiency and low noise. In the present paper, a SWATH-shaped USV designed for monitoring of protected coastal regions is numerically studied solving the Navier-Stokes equations on the fully appended vessels with several environmental conditions. An accurate hydrodynamic characterization will presented in order to investigate its performances and eventual maneuverability issues.

Keywords: SWATH; UAV; CFD; Intereference Factor

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1. Introduction

The high costs associated with the use of research oceanographic vessels and the maturity of the unmanned surface vehicles (USV) makes now possible to develop systems for monitoring coastal areas based on networks of independent USVs. CNR-INSEAN, in the framework of USV PERMARE research project, aims to develop a system based on USV units able to launch and recover autonomous vehicles of different nature (gliders, AUVs, motor-gliders, wire-guided ROVs), and to acquire environmental data (in the column water from free-surface to the sea floor), in order to meet the requirements of civil and military applications. The cutting-edge aspects that characterize the project are:

- the non-conventional hull design consisting in a SWATH (Small Waterplane Area Twin Hulls) configuration, optimized so as to ensure an unique seakeeping (higher operation capability) and a reduced resistance (higher autonomy);
- the propulsion system with propellers in mantle, developed to combine propulsive efficiency (reduced installed power) and low noise (higher efficiency in measurements).

The integrated system of autonomous units proposed allows to increase the volume of sea inspected. In facts, a significant number of slow-moving vehicles can satisfy two crucial requirements:

- high autonomy;
- high-resolved domain sampling.

The aim of this research project is the development of a reduced-size platform ensuring high stability even with adverse sea state. The development of a non-conventional hull design, based on a SWATH configuration, minimizes hull cross section area at the sea's surface and, consequently, maximizes the stability, even at high speeds. Nevertheless, the project is aimed to increase the stability developing an active stabilization system that is effective at all operational speeds, stationary condition included.

The developed platform must be able to operate as a baseship for complex underwater systems: the platform must support the sub-vehicles take-off and landing and it must be able to acquire all the measurements performed and to forward them to a remote control station for the data processing. The project is aimed to develop the prototype from scratch. It has been chosen to adopt a numerical design approach: starting from a baseline layout, many numerical tools are employed to improve (optimize) the design in order to satisfy the project specifications. In particular, an accurate hydrodynamic characterization of the baseline design is necessary for fueling the hydrodynamic optimization, see Zaghi et al. (2015). In this work, the preliminary results of hydrodynamics characterization of the USV PERMARE SWATH are reported.

1.1. Mathematical and Numerical Models

To accurately predict the flow generated around the SWATH vessel the (steady and unsteady) Navier-Stokes equations are solved by means of χnavis, a numerical solver developed at CNR-INSEAN. Within the assumption of an incompressible fluid, the set of equations is written in non-dimensional integral form with respect to a moving control volume V as

$$\oint_{S(\mathcal{V})} U \cdot \nu dS = 0$$
$$\rho \frac{\partial}{\partial t} \int_{\mathcal{V}} U dV + \oint_{S(\mathcal{V})} (\mathcal{F}_c - \mathcal{F}_d) \cdot \nu dS = 0 \qquad (1)$$

The equations are made non dimensional by a reference velocity (typically the free stream velocity U_{free}) and a reference length l_0 and the water density ρ. In equation (1), $S(V)$ is the boundary of the control volume, and v the outward unit normal; F_c and F_d represent Eulerian (advection and pressure) and diffusive fluxes, respectively:

$$\mathcal{F}_c = p\overline{\overline{I}}\rho(U - V)U$$
$$\mathcal{F}_d = \frac{\rho}{Re}\left[grad(U) + grad(U)^T\right]$$

where $U = (u_1, u_2, u_3)$ is the fluid velocity and V the local velocity of the boundary of the control volume. In the above equations, ρ is the fluid density, $p = P + \rho r\, z/Fr^2$ is the hydrodynamic pressure, i.e. the difference between the total P and the hydrostatic pressure z/Fr^2 , g being the acceleration of gravity, parallel to the vertical axis z (positive upward).

1.2. Numerical method

The numerical solution of the governing equations is computed by means of an in-house solver that yields the numerical solution of the unsteady Navier-Stokes equations with proper boundary and initial conditions. It is formulated as a finite volume scheme, with variable co-located at cell centres. Free surface effects are taken into account by a level-set algorithm. Complex geometries and multiple bodies in relative motion are handled by a suitable dynamical overlapping grid approach; high performance computing is achieved by an efficient shared and distributed memory parallelization.

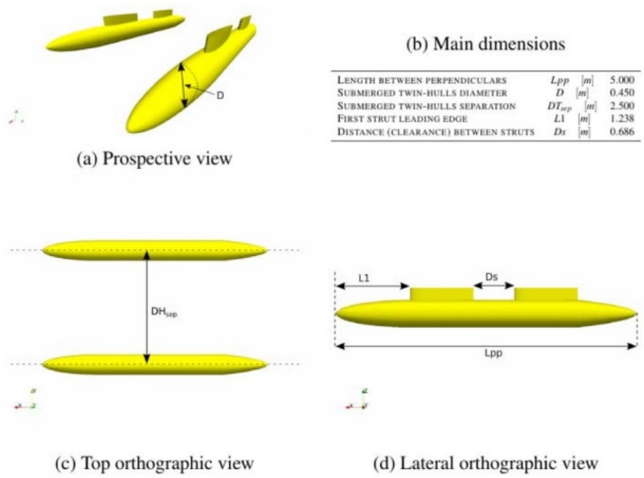
1.3. Overlapping grids approach

In order to cope with complex geometries or bodies in relative motion, the numerical algorithms were discretized on a block structured grid with partial overlapping, possibly in relative motion. This approach renders domain discretization and grid quality control much easier than with analogous discretization techniques implemented on structured meshes with abutting blocks. Of course, grid connections and overlapping are not trivial, as with standard multi–block approaches, but must be computed in advance. The detailed description of the algorithm used can be found in [5, 4, 1, 7].

2. SWATH Design

The USV PERMARE SWATH (Small Waterplane Area Twin Hull) is designed as a two submarine hulls connected to the upper platform by a couple of twin narrow struts from each of the submarine hulls (for a total of 4 struts). The SWATH configuration has been chosen in fulfillment of the USV PERMARE design specifications: high stability and reduced resistance (reducing the energy consumption). As a matter of facts, the SWATH configuration minimizes hull cross section area at the sea's surface. Minimizing the ship's volume near the surface area of the sea, where wave energy is located, increases the vessel's stability, even in high seas and at high speeds.

Figure 1 shows an overview of the main dimensions of the baseline SWATH design. Table 1b summarizes the SWATH main dimensions. Despite of the simplicity of the baseline layout, many parameters are involved into the final hydrodynamic characterization of the vessel (thus they being relevant for the baseline optimization), in particular (keeping fixed L_{pp}): 1) the twin-hulls separation and 2) the struts clearance. This 2D optimization-parameters domain is currently under investigation. In this preliminary work, only the hydrodynamic characterization of the baseline design is reported; in addition some results including control surfaces are reported as well.



Length between perpendiculars	Lpp	$[m]$	5.000
Submerged twin-hulls diameter	D	$[m]$	0.450
Submerged twin-hulls separation	DT_{sep}	$[m]$	2.500
First strut leading edge	$L1$	$[m]$	1.238
Distance (clearance) between struts	Ds	$[m]$	0.686

Fig. 1. SWATH geometry overview.

3. Numerical Setups

For the purpose of hydrodynamic characterization the tests matrices reported in table 1 has been simulated by means of the χnavis numerical simulation tool. Model-scale conditions considered, assuming fresh water characteristics, are: 1) $\rho[kg/m^3]=999.103$; 2) $g[m/s^2]=9.80665$; 3) $\nu[m^2/s]=1.139\cdot10^{-6}$; 4) $\sigma[N/m]=7.280\cdot10^{-2}$. Exploiting the flexibility of the chimera overlapping grids a high-quality body-fitted mesh has been realized. Figure 2 shows an overview of the main topologies realized.

The grid is composed by 92 partially overlapping blocks, for a total of about 5.6 millions of finite volumes. The blocks are subdivided into 4 main groups: 1) Background blocks having Cartesian topology; 2) free surface capturing blocks having Cartesian topology; 3) hull blocks having O-grid topology; 4) struts blocks having C-grid topology.

The boundary layer is well resolved, the grid resolution is clustered to wall with normal spacing ensuring $y+\leqslant1$ for all the Reynolds numbers considered. The boundary conditions imposed are: symmetry for the plane y=2.5m in order to simulate the presence of the two twin submarine hulls, uniform inflow condition for the plane at x=0 and outflow (non reflecting) boundary condition for all other boundary planes. The free surface is captured by a one phase level set approach, see the appendix on χnavis solver for more details.

Table 1. Tests Matrix: fresh water conditions.

Inflow velocity U_0 [knot]	Inflow velocity U_0 [m/s]	Froude number F_r	Reynolds number R_e	Weber number W_e
1.0	0.514	0.073	$2.259 \cdot10^6$	$1.347 \cdot10^2$
2.0	1.029	0.147	$4.518 \cdot10^6$	$2.695 \cdot10^2$
3.0	1.543	0.220	$6.777 \cdot10^6$	$4.042 \cdot10^2$
4.0	2.058	0.294	$9.036 \cdot10^6$	$5.390 \cdot10^2$
4.5	2.315	0.331	$1.016 \cdot10^7$	$6.064 \cdot10^2$
5.0	2.572	0.367	$1.129 \cdot10^7$	$6.738 \cdot10^2$
5.5	2.829	0.404	$1.242 \cdot10^7$	$7.411 \cdot10^2$
6.0	3.087	0.441	$1.355 \cdot10^7$	$8.085 \cdot10^2$

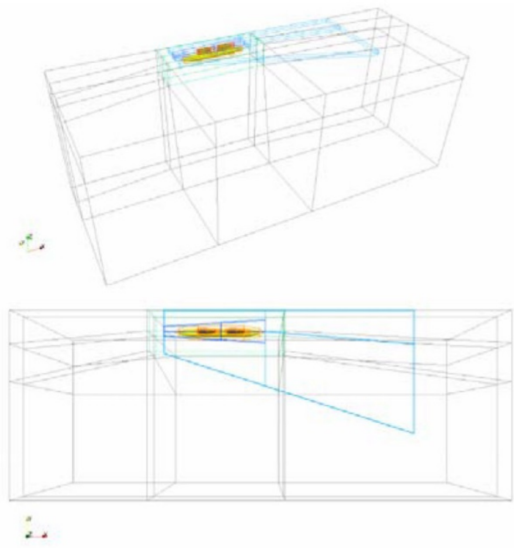


Fig. 2. Topology overview: black far background, light green near background, light blue free surface, orange hull, red struts.

For evaluating the interference effects between the twin submarine hulls of the SWATH a second numerical mesh (strictly related to the above described one) has been constructed for simulating only one, isolated, submarine (hereafter referred as demi SWATH configuration). This second mesh is essentially the same of the previous one, except for the background and free surface groups. The hull and struts groups are identical to the previous one (obviously only the left symmetrical half has been used), whereas the symmetry plane is placed at y=0. Consequently, the background and free surface grids groups are trimmed out of the blocks discretizing the domain for y>0.

3.1. Simulation Conditions

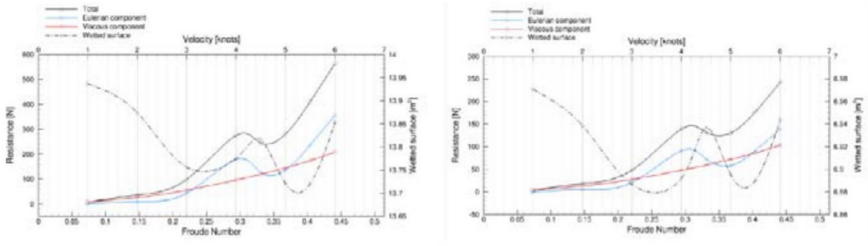
For all the numerical simulations of the test matrix reported in 1 uniform inflow conditions have been considered. The undisturbed free stream is at rest and the SWATH has a fixed attitude. The SWATH has no trim (zero angles of pitch, drift and roll) and the sinkage is fixed at 0.425m. The numerical simulations have been performed in non dimensional quantities. The following non dimensional numbers have been considered: Reynolds number, $Re=UL/\nu$ and Froude number, $Fr=U/\sqrt{gL}$. The reference values considered are: 1) reference density, $\rho_0=10^3$ [kg/m^3] the density of the free stream; 2) reference velocity, U_0 the free stream inflow velocity, varying in $1\text{kn}\leqslant U_0\leqslant 6\text{kn}$; 3) reference length, L_{pp}=5m the length between perpendiculars of the submarine; 4) reference area, $L_{pp}^2=25\text{m}^2$; 5) reference pressure, $\rho_0 U_0^2$; 6) reference force, $\rho_0 U_0^2 L_{pp}^2$.

4. Preliminary Results

In the following some preliminary results of the hydrodynamic characterization are reported.

4.1. Resistance analysis

Figure 3 shows the resistance analysis for both complete and demi SWATH configurations. Table 2 reports the grid uncertainty analysis. The grid uncertainty has been estimated by Roache's method, $\text{Uncertainty}=|(R_{fine}-R_{coarse})/(4R_{fine}-R_{coarse})|$. The non optimal convergence, 7.35% numerical uncertainty, at low Froude numbers is due to very small free surface perturbations not accurately captured by the actual grid resolution: this does not influence the overall accuracy of the predicted resistance. Figure 4 shows the fresh water Interference Factor analysis that is defined as $IF=(R^c-2R^d)/(2R^d)$.



(a) Resistance analysis for Fresh Water Conditions: complete SWATH

(b) Resistance analysis for Fresh Water Conditions: demi SWATH

Fig. 3. Resistance analysis for Fresh Water Conditions: complete and demi SWATH.

Table 2. Resistance results [dimensionless] and verification analysis.

Inflow velocity U_0 [knot]	Froude number F_r	Coarse grid	Medium grid	Fine grid	Grid uncertainty [%]
1.0	0.073	$4.583 \cdot 10^{-4}$	$5.869 \cdot 10^{-4}$	$4.869 \cdot 10^{-4}$	7.35
2.0	0.147	$1.124 \cdot 10^{-3}$	$7.848 \cdot 10^{-4}$	$6.767 \cdot 10^{-4}$	5.62
3.0	0.220	$1.291 \cdot 10^{-3}$	$9.273 \cdot 10^{-4}$	$8.188 \cdot 10^{-4}$	4.62
4.0	0.294	$1.505 \cdot 10^{-3}$	$1.324 \cdot 10^{-3}$	$1.298 \cdot 10^{-3}$	0.65
4.5	0.331	$1.359 \cdot 10^{-3}$	$1.024 \cdot 10^{-3}$	$9.095 \cdot 10^{-4}$	4.40
5.0	0.367	$1.347 \cdot 10^{-3}$	$9.705 \cdot 10^{-4}$	$8.480 \cdot 10^{-4}$	4.06
5.5	0.404	$1.523 \cdot 10^{-3}$	$1.145 \cdot 510^{-3}$	$1.027 \cdot 10^{-3}$	3.97
6.0	0.441	$1.687 \cdot 10^{-3}$	$1.303 \cdot 10^{-3}$	$1.210 \cdot 10^{-3}$	2.65

Where the IF is negative there is constructive interference, see [2, 6]. The wave pattern plays a crucial role, the interference being due to the Eulerian component of the resistance. Both complete and demi SWATH configurations show a local minimum of resistance close to U=4.5kn, Fr=0.35. For both complete and demi SWATH configurations the resistance behavior is strongly related to the Eulerian component, i.e. the wave pattern plays a crucial role for the hull design optimization. Relevant differences can be highlighted especially for the Eulerian component of the Resistance and for the wetted surface behavior.

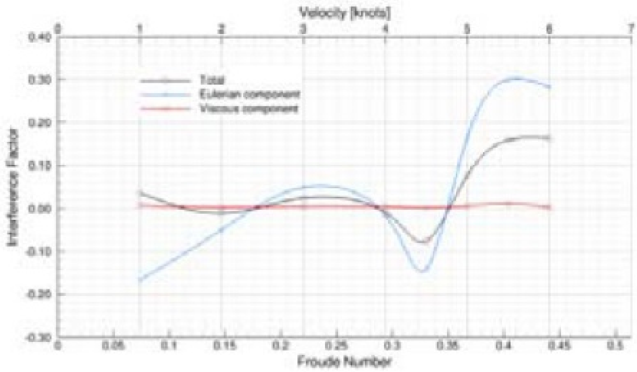
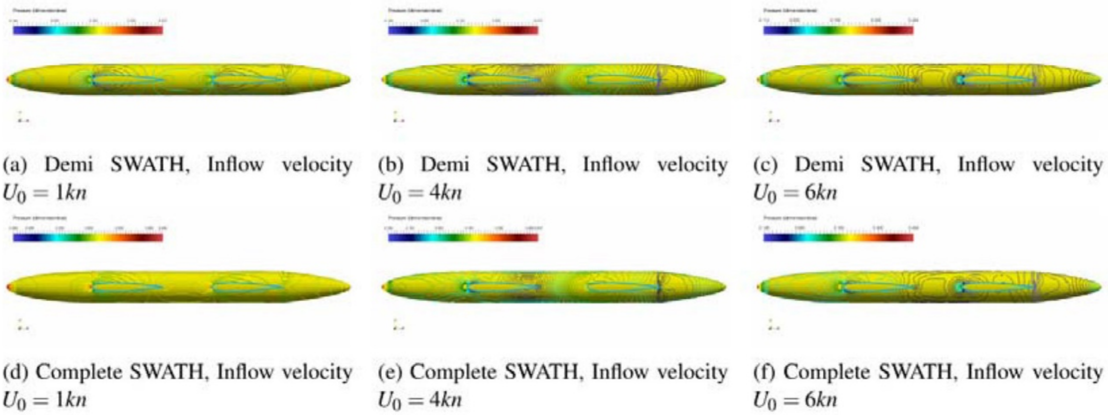


Fig. 4. Interference Factor analysis.

4.2. Surface pressure analysis

Figure 5 shows a comparison of the wave pattern for all the conditions considered for the demi SWATH configuration. As expected, the struts clearance plays a crucial role for the surface pressure field: as the velocity increases a local low-pressure region happens in-between the struts due to their mutual interaction. In particular the local minimum happens close to 4.0kn. It is worth noting that close to same velocity, about 4.5kn the twin hulls interference endures a local minimum (constructive interference) thus highlighting this regime for further optimization.

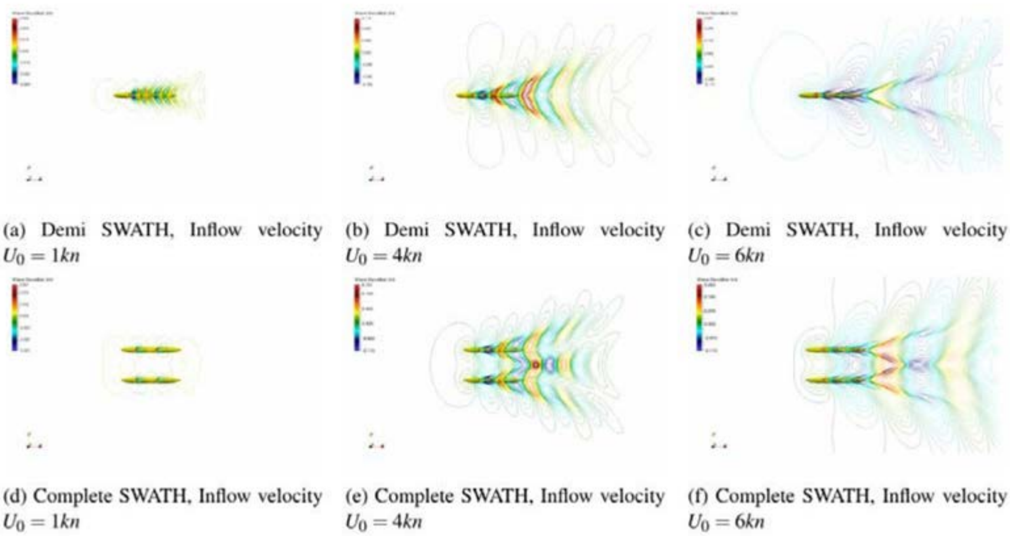


(a) Demi SWATH, Inflow velocity $U_0 = 1kn$
(b) Demi SWATH, Inflow velocity $U_0 = 4kn$
(c) Demi SWATH, Inflow velocity $U_0 = 6kn$
(d) Complete SWATH, Inflow velocity $U_0 = 1kn$
(e) Complete SWATH, Inflow velocity $U_0 = 4kn$
(f) Complete SWATH, Inflow velocity $U_0 = 6kn$

Fig. 5. Surface iso-pressure contours for the demiand complete SWATH configurations.

4.3. Wave patterns analysis

Figure 6 shows a comparison of the wave pattern for all the conditions considered for the demi SWATH configuration. It is worth noting that the wave pattern strongly changes around 4.5kn where the twin hulls interference is relevant and constructive.



(a) Demi SWATH, Inflow velocity $U_0 = 1kn$
(b) Demi SWATH, Inflow velocity $U_0 = 4kn$
(c) Demi SWATH, Inflow velocity $U_0 = 6kn$
(d) Complete SWATH, Inflow velocity $U_0 = 1kn$
(e) Complete SWATH, Inflow velocity $U_0 = 4kn$
(f) Complete SWATH, Inflow velocity $U_0 = 6kn$

Fig. 6. Wave patterns comparison for the demi and complete SWATH configurations.

4.4. Control surfaces analysis

The study of the hydrodynamic performances of the full appended configuration (i.e. including the control surfaces) is also on going. Control surfaces consist of fore and aft planes, mounted in the inner part of each hull. The activity concerns the hydrodynamic analysis at one fixed speed (4Kn) and for several deflections of the control surfaces. Both static and dynamic deflections are considered. The full text matrix includes static deflections ranging from -20 ° to 20 ° of both fore and aft planes (singularly) and an oscillatory deflection at fixed frequency and amplitude (to be decided). Preliminary results are reported in figure 7, where an overview of the limiting streamlines colored with the surface pressure is reported for the case with fixed deflection of the control surfaces.

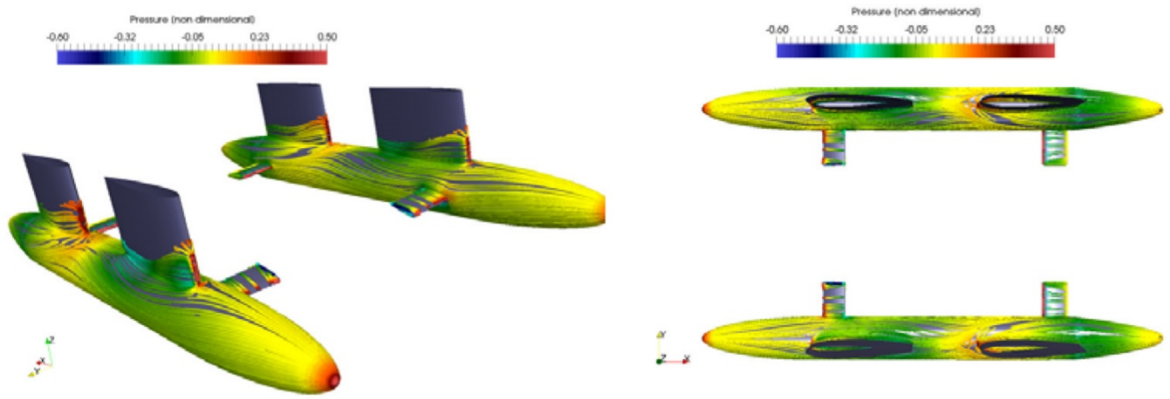


Fig. 7. Swath in fully appended configuration. Limiting streamlines colored with surface pressure.

5. Conclusions

The present paper reports the ongoing activities that CNR-INSEAN is doing in the framework of the USV PERMARE research project. The preliminary results of the hydrodynamic characterization of an innovative unnamed surface vehicle based on a SWATH configuration are reported.

The presented results have shown a constructive interference around 4.5kn. As expected, the wave resistance is relevant. As a matter of facts, for both complete and demi SWATH configurations the resistance behavior is strongly related to the Eulerian component, i.e. the wave pattern plays a crucial role for the hull design optimization. Relevant differences can be highlighted especially for the Eulerian component of the Resistance and for the wetted surface behavior. The baseline design has been considered, whereas optimized one is currently under analysis and will be reported in future works.

Acknowledgements

This work was supported by Distretto Ligure delle Tecnologie Marine (DTLM) under the research project USV PERMARE, funding of Ministry of Education and Research (MIUR, grant DM62573).

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