HYDRODYNAMIC DESIGN OF A FAMILY OF HYBRID SWATH UNMANNED SURFACE VEHICLES

S. Brizzolara, M. Bovio, A. Federici, and G. Vernengo

MITSG 11-21
Hydrodynamic Design of a Family of Hybrid SWATH Unmanned Surface Vehicles
Stefano Brizzolara¹, Marco Bovio¹, Alessandro Federici², Giuliano Vernengo¹

¹ Marine CFD Group, Dept. of Naval Architecture, Marine and Electrical Engineering, University of Genoa, Italy
² University Pole of La Spezia for Yacht Design, La Spezia Italy

ABSTRACT
Papers presents the concept designs of two autonomous marine vehicles belonging to a new family of unconventional SWATHs optimized for low resistance at high speeds. The focus is concentrated on the prediction of the hydrodynamic characteristics and the optimization methods used to design the hull forms in order to minimize the propulsion power at the operational speed of the vehicles. For both vessels a modern automatic parametric optimization computer based procedure has been developed and RANSE calculations performed to validate the final design. The second vessel, is a hybrid SWATH, capable of reaching a top speed of 120 knots in the foil-born mode, at which four supercavitating hydrofoils are folded down into water. Main issues related to the design of surface piercing super-cavitating hydrofoils, for operation at such a high speed, are presented and discussed on the basis of the results obtained through CFD simulations and feedback from preliminary results of model tests in cavitation tunnel.

KEY WORDS
Fast SWATH, Unmanned Surface Vehicles (USV), Super-cavitating Hydrofoils, CFD, ground effects.

1.0 INTRODUCTION
Hydrodynamic design and optimization of innovative Unmanned or Autonomous Surface Vehicles (USV/ASV) is a recent interesting research branch in naval architecture. In fact, taking inspiration from the earlier developments made by the aero-space engineering research community, unmanned marine vehicles have opened new possibilities of performing complex operations thanks to their broader operational capabilities. The advantages of being unmanned, though, must be synergically enhanced with an unconventional design of the craft, optimized to the scope, so to achieve mission objectives once unimaginable or still extremely demanding or hazardous for manned vessels.

Beside the driving prevalent military interest, in these last few years also the marine research community has focused on ASVs, after the release of open source software, such as MOOS-IvP for the control intelligence and the commercial availability of economic and compact localization and communication systems. A good review of current technology in this field is collected by Huntsberger, Keegan and Brizzolara (2010 and 2011). Examples of marine research AUVs recently built or under development are numerous and diverse, but in the whole they are designed with the main focus on the electronic apparatus and logic for autonomy, while they appear less optimized for what concerns the hull, that is more often adapted from off the shelf recreational small crafts, not specifically designed for the best hydrodynamic performance.

In this panorama, the authors have teamed up for the development of two USV designs for diverse applications: one is a small (6m long) vessel devised for the autonomous launch and recovery of AUV in coastal area, the other is a medium sized superfast vehicle for offshore search and rescue. The two USV are different in size and operational speed, but the idea behind the hull definition derives from the same unconventional SWATH family of hulls, able to minimize the advance resistance and obtain favourable propulsive power also at relatively high speeds. The next section will present the concepts that are behind the family definition, while the next two sections will present two examples of ASV design.

2.0 THE NEW ASV-SWATH FAMILY
The general concept behind the new ASV family definition is the unconventional high speed hybrid SWAT-Hulls, particularly suitable to reach (in displacement mode) relatively high speeds, corresponding to length Froude number $Fn=0.8$. Figure 1 gives an idea of the speed/length relation for two vessels of the family, presented in the paper.

![Figure 1 – Size and speed of the two USV of the family](image-url)
The first vessel has a length of 6m and a design speed of 12 knots, while the second has two 20m long underwater hulls and a max speed in displacement mode of about 25 knots.

The reason to use a SWATH also for a fast vessel is the well known superior seakeeping ability in relatively high sea states, with respect to other conventional displacement hull typologies. The main drawback of SWATHs, however, has always been the higher powering requirement with respect to equivalent monohulls or catamarans, especially at the highest Froude numbers. Following the earlier work of Brizzolara (2004), use is made of an unconventional shape for the underwater hulls with two relative main sections and an intermediate contraction. It was found (Brizzolara, 2004) that the minimization of the resistance at a given design speed is primarily dependent on the position of the intermediate contracted section. Its position along the length changes as a function of Froude number; in general at lower speed the contracted.

The unconventional shape is found through a new automatic optimization procedure, based on a fully 3D parametric modeling of the hull surface and a viscous-inviscid flow solver.

3.0 SMALL USV-USWATH for AUV SUPPORT

Following the vision of Dr. Tom Curtin, chief scientist of NURC (NATO Undersea Research Center), the basic design of an innovative small ASV with Unconventional SWATH hull, represented in Fig.3, was developed (Brizzolara et al. 2011). Its prevalent mission is the transportation, launch and recovery of medium sized AUVs being used at the center (i.e. Folaga, Hydroid, etc.), but it is equipped also to autonomously take sets of basic measurements.

![Fig. 3. First version of the small USV](image)

In fact, after several decades of research and development in the field, collaborative systems of AUVs (Autonomous Underwater Vehicles) are nowadays an interesting option for implementing a persistent monitoring system of extended sea areas with an incomparable efficiency, both in terms of costs and operability. The majority of these vessels, though, is operating underwater (AUV) and requires the regular support of a manned ships at least to bring vehicles on place and to launch and retrieve them. An efficient and functional Unmanned Surface Vehicles (USV) is the key for a step-up in the actual operational capabilities of the autonomous sea persistent monitoring systems.

![Fig. 4. The small USV-SWATH as the key element of an integrated cooperative AUV network](image)
3.1 Hull Form Design and Optimization

The SWATH hulls of the small USV presented in Fig. 2, belongs to the family described in previous section (Fig. 1), reaching $Fn=0.8$, at the design speed of 12 knots. The main characteristics of the lower hulls are listed in Table 1, together with those of the second vessel of the family (ONRG) and those of an optimization made some years ago for a SWATH passenger ship (Brizzolara, 2004). The unconventional shapes of these three lower hulls indeed result to be very similar, confirming that for $Fn>0.5$ the position of the contracted section remains almost invariably at midship, independently from the prismatic coefficient $CP$ and from the slenderness coefficient $L/V^{1/3}$ or ratio $L/D$.

Table 1. Characteristics of the lower hulls of the two USVs

<table>
<thead>
<tr>
<th></th>
<th>L/D</th>
<th>CP</th>
<th>$L/V_1$</th>
<th>$L/V_{tot}$</th>
<th>$Fn$</th>
<th>$Fn_{V1}$</th>
<th>$Fn_{Vtot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH04</td>
<td>13.3</td>
<td>0.65</td>
<td>7.04</td>
<td>4.89</td>
<td>0.50</td>
<td>1.32</td>
<td>1.10</td>
</tr>
<tr>
<td>NURC</td>
<td>10.0</td>
<td>0.55</td>
<td>6.15</td>
<td>3.74</td>
<td>0.80</td>
<td>2.00</td>
<td>1.56</td>
</tr>
<tr>
<td>ONRG</td>
<td>16.7</td>
<td>0.42</td>
<td>9.44</td>
<td>5.80</td>
<td>0.92</td>
<td>2.82</td>
<td>2.21</td>
</tr>
</tbody>
</table>

Design constraints on maximum weight and dimension were assigned to guarantee the manageability and transportability of the vehicle on land and offshore. This resulted in rather short hulls ($L=6m$), so the sufficient initial transversal and longitudinal metacentric height were obtained adopting a twin canted design for the struts and positioning them at the extreme bow and stern of the vessel as from Fig. 3.

Fig. 5. B-Spline S-shaped generatrix curve used to define lower bodies with contracted intermediate section

Having fixed the struts, the underwater hulls shape has been optimized with a new parametric optimization procedure. The hull form has been reproduced using a parametric modeller (Friendship), on the basis of a minimum set of parameters defining the unconventional S-shaped generatrix curve defined by 7 points, as from Fig. 5. The hull surface is an ellipsoidal B-Surface obtained on the basis of the generatrix curve and with elliptical sections having a given ration for the minor/major radii. The free parameters are the coordinates of the three internal points (2,3,4) that control the contracted section shape and the vertical distance of the copy of leading and trailing edge points that control the two curvature radii in those positions. Original and optimized values are listed in Table 2, together with those of the conventional solution taken from series 58 (with the same prismatic coefficient).

An automatic computational procedure driven by a global convergence algorithm (of the evolutionary strategy type) was created. It iteratively selects a set of free parameters, from which a 3D SWATH geometry (3D surface and quadrilateral panels subdivision) is generated and the flow around it evaluated by the viscous-inviscid solver to eventually converge on the optimum shape, i.e. the one that is able to minimize the objective function. To speed up the calculations only wave resistance was considered in the objective function, taking care of setting maximum upper limits to the variation of the curvature radii at the leading and trailing edge of the lower hulls, which are the main responsible of a change in viscous resistance (Brizzolara, 2004).

Table 2. Free parameters defining the original, conventional and optimized lower hulls geometries, with respective values of the predicted wave resistance coefficients

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optim.</th>
<th>Original</th>
<th>Conv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>0.052</td>
<td>0.24</td>
<td>0.15</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.675</td>
<td>0.40</td>
<td>0.60</td>
</tr>
<tr>
<td>$X_3$</td>
<td>0.876</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>$Z_1$</td>
<td>0.297</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>$Z_2$</td>
<td>0.746</td>
<td>0.65</td>
<td>0.30</td>
</tr>
<tr>
<td>$Z_3$</td>
<td>0.126</td>
<td>0.24</td>
<td>0.65</td>
</tr>
<tr>
<td>$Z_4$</td>
<td>0.838</td>
<td>0.74</td>
<td>0.60</td>
</tr>
<tr>
<td>$Z_5$</td>
<td>0.399</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>$V_1$ (m³)</td>
<td>4.049</td>
<td>4.080</td>
<td>4.268</td>
</tr>
<tr>
<td>$C_w10^4$</td>
<td>1.915</td>
<td>3.336</td>
<td>3.533</td>
</tr>
<tr>
<td>$\Delta C_w$ %</td>
<td>-45.8</td>
<td>-5.6</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Fig. 6. Conventional (top) original and optimized (below) shapes for the underwater bodies of the small USV-SWATH

Fig. 7. Predicted wave resistance coefficient during automatic optimization procedure
Fig. 9 shows the value of the predicted wave resistance coefficient for each of the 1000 evaluated hull forms, showing a good convergence property of the selected evolutionary algorithm. Discarding the points, far from the main trend line, whose result are normally due to singularities in the automatically generated free surface or hull meshes, it is possible to select the optimum case reported in Table 2. The wave resistance in this case is reduced by about 45% with respect to the conventional solution and about 40% on the initial guessed shape which was not really optimal.

More accurate predictions of propulsive performance and \textit{ad hoc} propeller design could be made with exact RANSE prediction and fully numerical propeller design method as already done with success by Brizzolara & Gaggero (2010) in case of the OEX AUV.

3.2 General Arrangements and Functionality

Fig. 7 shows a 3D-view of the general arrangement of the small USV-SWATH. The propulsion is diesel-electric with two gen-sets of 25kWe in the upper body, two fast DC brushless electric motors of 20 kW each in the lower hulls connected through epicycloidal gears to the slow turning propellers. Four battery packs are fitted in the lower part of the struts. Fuel and symmetric ballast tanks are fitted in the central portion of each lower hull to grant a range of about 120 miles.

The central portion of the upper structure, delimited by two watertight bulkheads is hosting the recovery, launching and recharging system for AUVs (one of typical size is represented inside the docking station in Fig. 9). The vessel is also equipped with two pairs of stabilizer fins fitted at the bow and stern of each lower hull, singularly regulated by an integrated ride control system to correct the dynamic trim and sinkage at full speed and to dampen roll, pitch, yaw motions in waves.

It is to be noted that the upper main body is watertight and structurally connected to the struts through a dismountable series of tensioned threaded rods, that can be registered. Also the lower hull and struts are watertight and structurally independent. So the vehicle can be dismounted and transported in pieces arranged into a standard container.
4.0 ULTRAFAST HYBRID HYGE-SWATH

This second autonomous vehicle has a very particular mission profile, specified in the BAA-10-001 of the Office of Naval Research: a concept design of a marine vehicle capable of reaching a top speed of 120 knots, with a total range of 500 miles to be achieved in at least two trips. In addition, the vessel must be capable of loitering at low speed for several hours, maintaining its operability up to sea state two. In response to this request a new vessel of the family of unconventional high speed SWATHs was devised and after several alternative options, the final design has converged on the solution presented in the artistic views of Fig. 10 and Fig. 11. The vessel is about 20m long, 16m wide and 5.5 meter high at the level of the cross deck bottom for a full load weight of about 42 tonnes.

The research project, which is currently still on-going, has completed the design of all the main components and already assessed through CFD methods some of the aero/hydro dynamics of the hull and hydrofoils.

![Image](https://example.com/image.png)

**Fig. 10.** 3D view of the concept design of the Ultrafast USV

A new acronym was devised to include the main three concept behind this innovative vessel: HYGE-SWATH: HYdrofoil Ground Effect SWATH.

In displacement mode (top picture of Fig. 11) the hydrofoils are folded up against the struts and the vessel is a SWATH with the a similar design of unconventional lower hulls as described for the previous USV, but with twin counter-canted struts (see view of Fig. 10).

For reaching the top speed of 120 knots, the two turbo-jet engines are started and two pairs of surface-piercing hydrofoils are folded down at about 40 degree with the horizontal plane and the vessel is transformed into a surface piercing hydrofoil. In this operating mode, called the foilborn mode, the weight of the vessel is sustained in its major part by the four super-cavitating hydrofoils, while the rest of the lift required force is developed by the trapezoidal wing shaped superstructure with a rather good efficiency. In fact, the cambered superstructure travelling at 120 knots close to the sea surface can exploit a ground effect, which increases the efficiency in terms of lift to drag ratio. A proper compromise of the share of lift between hydrofoils and wing should not only consider the maximum efficiency, but also the vessel’s dynamics in rough sea conditions, due to unsteady forces transmitted by waves and wind on the vessel’s hull and superstructure.

The challenges in the design of the optimum SWATH and those related to the supercavitating hydrofoils will be described in more details in the two next subsections.

![Image](https://example.com/image.png)

**Fig. 11.** 3D view of the concept design of the Ultrafast USV

4.1 Displacement Mode: hull form optimization

The lower hulls of this vessel are belonging to the family of unconventional hulls described in section 3.1 and in fact their main geometric characteristics have been optimized in a similar way, considering the take-off speed of 25 knots, corresponding to Fn=0.9. Being the Froude number not so different from the previous USV, the unconventional shape of the lower hulls is fairly similar, although they are more slender and finer (see Table 1).

The optimization studies, in this case, have considered also the best layout of the struts, which was not considered in the previous design.

In fact, one of the intermediate design versions of this new vessel (v.3.3), represented in the left column series of picture of Fig. 12, the two struts on each side of the vessel were designed in-line and with a vertical stem in the submerged part. From free surface RANSE simulations, made with a successfully validated numerical model already tested in case of unconventional SWATH (Brizzolara & Villa, 2009), it was found that the major part of the resistance at a speed close to take-off (Fn=0.66) is concentrated in the aft struts. This is due to the large interference effect between the waves generated by the forward strut onto the stern one, as arguable from the series of picture in the first column of Fig. 12.

In order to reduce the resistance on the aft strut, the effect of the canting angle and the sweeping angle were investigated,
keeping the same transverse section of the strut, and keeping a sufficient inertia moment of the design waterplane.

A good compromise in terms of design constraints and resistance reduction was achieved in a subsequent version of the vessel, v.4.1, in which the fore struts were inclined of 20 degree inward angle (going upwards) and the stern ones of an equal but opposite angle (outward). The CFD results obtained for this version are presented in the right column of Fig. 12: from the comparison of the two different struts layouts, it can be clearly noted that the counter-canting is able to bring the wave peak generated by the fore strut off the stem of the aft one, and at the same time the forward sweep of the stem, combined with the horizontal spray rail (same shape of v.3.3) are able to rise less spray than v.3.3. According to RANSE predictions, version 4.1 results to have a reduction in total resistance of about 20% than version 3.3. So the typology of struts seems important for high speed double struts SWATHs.

Fig. 12. Free surface deformation predicted with RANSE model of two different version of HY-GE-SWATH at Fn=0.66. Left column: v.3.3 with inline vertical struts. Right column: v.4.1 with counter-canted swept forward struts.
4.2 Foilborn Mode: super-cavitating hydrofoils

Surface piercing hydrofoils have been selected for sustaining the vessel at high speed, in order to give an inherent stability to the vessel without the need of sophisticated actuation systems to regulate the foils’ lift. A negative dihedral angle was chosen for the surface piercing foils, as visible in Fig. 10 or Fig. 11. This choice tends to further increasing the stability of the vessel in foilborn mode with respect to a more usual positive dihedral angle layout, such as that used in conventional surface piercing hydrofoils developed in different part of the world after the first Raketa Russian class. Due to the extremely low cavitation number \( \sigma_0=0.05 \) reached at top speed, the hydrofoil will be super-cavitating or ventilating from the free surface.

![Fig. 13. New Hybrid super-cavitating profile with annex working in design conditions (\( \alpha=5 \) deg, \( \sigma_0=0.05 \), \( L/D=12 \))](image)

The design and study of the super-cavitating hydrofoils posed several challenging research subjects, that would merit a continuation also after the end of the current research project. Not much research attention has been paid in this field after the pioneer theoretical/experimental works made in USA around ‘50-’70. Potential flow panel methods have been adapted to solve super-cavitating profiles and eventually applied with good success solely on propeller blades that are normally using thinner sections and working at not so extreme cavitation numbers (Young and Liu, 2008; Gaggero & Brizzolara, 2009). However, a rather systematic approach to the problem was planned in this research: first, a state of the art CFD solver was tuned and validated against available experimental results on supercavitating 2D hydrofoils with satisfying results (Brizzolara & Federici, 2011). Then the classic linearized theories for designing 2D super-cavitating profiles developed by Johnson in the ’60s were revamped and used to design some basic 2D profile shapes to be used as sections of the 3D hydrofoil. The performance of the two/three terms 2D profiles designed with Johnson’s method have been successfully verified with RANSE. A hybrid design procedure was developed that uses the conformal mapping theory to design the pressure side and a systematic use of RANSE calculations to define also the suction side of the 2D hydrofoil (Brizzolara & Federici, 2011), since the back shape is not considered by the original asymptotic theory, but it is actually important for strength and stability issues on the foil.

With the hybrid design method, a new supercavitating profile with annex, presented in Fig. 13 was designed. The new profile has a larger inertia modulus and a better efficiency and lift in partially or sub-cavitating conditions, such as those during take-off, than conventional truncated sections. From RANSE simulations (Fig. 13) the new profile lift is able to achieve a lift to drag ratio \( L/D=12 \) at top speed, but also a very good \( L/D=26 \) in non-cavitating conditions, i.e. during take-off; rather differently from conventional blunt base sup.cav. profiles, which have a maximum efficiency around 4 in sub-cavitating conditions.

On the base of this new profile a 3D hydrofoil, showed in Fig. 14, was design by a new lifting line design method developed to find the optimum distribution of circulation along the span of surface piercing hydrofoils with approximate effects of winglet, free-surface, sweep and dihedral angles. Strength is an issue in the design of these hydrofoils. The first version of the hydrofoil, in fact, is composed by a main foil, a short strut to reinforce the root connection and a stay attached to the foil face above the design water line to unload part of the lift force which would cause a too large bending moment at local stations. This solution is able to achieve an efficiency in terms of Lift to Drag ration of about 8.0 which is considerably good considering the rather low aspect ratio of the foil part submerged at design condition (Fig. 14).

![Fig. 14. The first version of the supercavitating hydrofoil at its mean design submersion at full speed](image)

The possibility of simulating, by RANSE numerical solvers, the three phase flow (air, water, vapour) around the surface piercing hydrofoil was finally explored. The current result is presented in Fig. 15 for the design condition, which shows vapour and air free limiting surfaces around the hydrofoil at design condition. The results are promising but still not satisfactory: in fact the air ventilation occurring on the back of the profile is not well capture: this fact translates into an overestimation of the lift force with respect to the experiments. The comparison with model tests which are currently under completion at the free surface cavitation tunnel of the Technical university of Berlin (TUB) shows an overestimation of about 13% of the RANSE model: a careful insight indicated that this numerical overestimation is totally due to the inaccurate numerical prediction of the ventilation phenomena on the back of the foil which results to be subject to vapour pressure, which is lower than the atmospheric pressure.
Future studies will continue the design and validation by CFD experiments of the supercavitating surface-piercing hydrofoils to increase RANSE simulation accuracy and further improve theoretical design methods. As regards the vessels research will focus on the unsteady hydrodynamics of the vessel, such as seakeeping of U-SWATH with active lifting surfaces, as well as the dynamic behaviour during take-off and landing and in wind and waves of the HY-GE-SWATH.

REFERENCES
Johnson, Virgil E, Jr (1960) Theoretical and Experimental Investigation of Supercavitating Hydrofoils Operating Near the Free Water Surface. NASA tech report no.199802284482

ACKNOWLEDGEMENTS
Special thanks to Dr. Tom Curtin who, in his period as chief scientist of NURC (NATO Undersea Research Center of La Spezia), pushed the Marine CFD Group of the Univ. of Genoa into this new research branch, competently assigning design specification for the small USV-SWATH, and expertly driving the developments with precious hints of innovation.

The studies on the super high speed USV, are being carried out under research grant N62909-10-1-7116 of the Office of Naval Research, dedicated to the “Hydrodynamic Design and Assessment by CFD Methods of Hybrid SWATH/Hydrofoil Hulls for a Super High Speed USV.

5.0 CONCLUSIONS
The hydrodynamic characteristics and design method of an a new family of high speed SWATH unmanned vehicles, having unconventional underwater hulls for with contracted intermediate section type, with two struts each have been described in the paper with reference to two particular individual of the family: one small USV for AUV support and one large size ASV for super high speed.

The particular hull forms permits to reach relatively high Froude numbers (Fn=0.8-0.9) with limited powering requirement in displacement conditions, overcoming the usual difficulty of conventional SWATH vessels. The optimized counter-canted struts configuration of the HY-GE-SWATH ultrafast speed vehicle has been also discussed on the basis of systematic RANSE simulations. Such a good layout of the struts can decrease the total hull resistance of more than 20%, at high speed.