Drag based Shape Optimization of Submarines and AUVs Using CFD Analysis

Cdr. Gianpaolo Damiano BONO[a,1] and Lt. Gianni BUTTARO[a,2]
[a] *Submarines Department - Italian Navy General Staff*

Abstract. Nowadays, underwater vehicles have a wide range of applications both in military, scientific, commercial and security fields. Next to Submarines, Autonomous Underwater Vehicles (AUVs) are increasingly spreading thanks to their capabilities to carry out a significant variety of missions, including interacting with underwater infrastructures, coastal and underwater inspections, intelligence gathering, environmental and fish monitoring and, of course, research and fight against underwater threats.

One of the main performance characteristics of an underwater vehicle is its resistance curve. The estimation of this curve is a crucial factor in preliminary design phases in order to correctly choose and dimension the right propulsion plant and propeller and, in general, to reach operational requirements.

In the last decade, with the advent of higher computing power and robust algorithms, the application of Computational Fluid Dynamics (CFD) analysis is rapidly emerging as a fast, reliable and cost-effective tool in the assessment of the hydrodynamic performances.

The paper offers the implementation of a "virtual wind tunnel" based simulation and the influence of the hull and sail shape of an underwater vehicle. A simulation was conducted and the numerical results were validated by comparing them with the available experimental data obtained from the literature.

In the second part of the paper, several modern technologies related to the underwater sector were analyzed to identify their influence on the shape during the design phase of an underwater vehicle. Particular considerations were dedicated to the different positions and profiles of the sail allowed by the integration of the optronic periscopes. Further considerations were made on the shape of the bow necessary for the integration of sonars of different types and sizes. In conclusion, various tests were carried out in the simulation environment in order to detect the optimized solutions for each case studies.

Keywords. CFD, Joubert BB2, RANS, OpenFoam, Submarine, AUV, optimization, drag, Marina Militare Italiana.

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[1] Cdr. Gianpaolo Damiano BONO, Platform and Security Office, Submarines Department, Italian Navy General Staff, 4 Piazza della Marina, 00196 Rome, Italy; gianpaolod.bono@marina.difesa.it .

[2] Lt. Gianni BUTTARO, Technical and Safety Design Analysis Section, Submarines Department, Italian Navy General Staff, 4 Piazza della Marina, 00196 Rome, Italy; gianni.buttaro@marina.difesa.it .

1. Introduction

The prediction of Submarine or AUV hydrodynamic performances in the early stages of the design represents a crucial topic for the estimation of the drag and, consequently, for the optimization of the hull design. Indeed, drag necessarily influences important factors, such as, maximum speed, range and acoustic signature.

In the canonical design practice, this estimation takes place through the construction and experimentation of scale models by time-consuming and expensive towing tests in specialized hydrodynamic laboratories, aimed at collecting experimental databases to be processed by theoretical relationship. Furthermore, compared to the ships, there are not many benchmark geometries and relative available experimental data about underwater vehicles. In the last decade, with the advent of higher computing power and robust algorithms, the application of *Computational Fluid Dynamics* (CFD) analysis is rapidly emerging as a fast, reliable and cost-effective tool in the assessment of the hydrodynamic performances. The opportunity to create a CFD-based testing environment allows to replicate a standard set of hydrodynamic tests in order to investigate on different shape solutions both in the early stage of the concept design and in the later stage of the design process.

Looking towards the next generation submarines, *Platform and Security Office* of the *Submarines Department* of the *Italian Navy General Staff* is building up its own capability to estimate the drag of an underwater vehicle in order to optimize the hull design according to different operational requirements.

In this study, the numerical analysis were conducted on the *BB2 Submarine* [1] using an *Open Source* commercial CFD software, *OpenFoam*, and applying the incompressible *Reynolds-Averaged Navier-Stokes* (RANS) method, using hexahedral mesh in calculating the drag at a fixed vehicle velocity deeply submerged in open water. The geometry reference was a 4000 tons fully-appended diesel-electric attack submarine (SSK) design and the available results of the "*NATO AVT-301 Collaborative Exercise: CFD Predictions for BB2 Generic Submarine, Phase 1 and 2*" [2] were used to validate the study.

Subsequently, the effects of the introduction of modern technologies and other payloads on an underwater vehicle were quantified using the CFD analysis (i.e. spherical sonars, optronic periscopes, acoustic target strength precautions and external payloads).

The study is focused on a Submarine model, but, given the similar geometries between Submarines and AUVs hull, all considerations may be taken in account for any underwater vehicle design.

2. Geometry

The reference geometry of this study was a 2 m model-scale (1:18.348) of the *BB2 Submarine* developed by the research institute *MARIN* with the aim of increasing the stability and control of a previous variant, *BB1 Submarine* [3][4]. The *BB1 Submarine* was developed by the *Defense Science and Technology Organization* (DSTO), on the concept design of *Joubert*, in order to identify a new shape for a SSK submerged able to assure a flexible interior volume with four decks, give the best possible flow over the forward passive sonar and move as silently as possible with a low practical resistance.

A view of the 3-D model is showed in Figure 1 and the main dimensions are proposed in the Table 1.

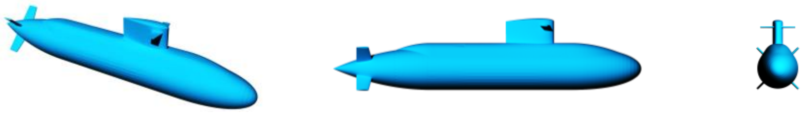

Figure 1. View of *Joubert* BB2 Submarine

Table 1. Main dimensions of BB2 model (model scale 1:18.348)

Quantity	Symbol	Value		Unit
		Full	Model	
Length overall	L_{oa}	70.2	2.0000	m
Beam	B	9.6	0.2737	m
Depth (to deck)	D	10.6	0.3020	m
Depth (to top of sail)	D_{sail}	16.2	0.4615	m

3. Non-Dimensional Force

The result force of the analysis in this study referred to the standard coordinate system where the *x* corresponds to the longitudinal axis of symmetry of the hull directed forward.

Force *X* was made non-dimensional *X'* with the length between perpendiculars L_{oa} of the submarine using:

$$X' = \left| \frac{X}{\frac{1}{2}\rho V_{\infty}^{2} L_{oa}^{2}} \right| \tag{1}$$

4. Computational setups

The simulation was performed using *OpenFoam 7* with the steady state solver *simpleFoam* and initialized with the potential flow solver *potentialFoam*.

The length of the domain was 15 × L_{oa} (10 × L_{oa} aft and 4 × L_{oa} forward the model) while width and height were both 5 × L_{oa}. The hexahedral mesh used, shown in Figure 2, had a high refinement close to the hull, characterized by 10 layers with an expansion ratio of 1.5 and an average non-dimensional wall distance of y^+=16.26, consisted in 10’216’957 cells and was modelled with a symmetry longitudinal plane in order to cut half of the computational cost.

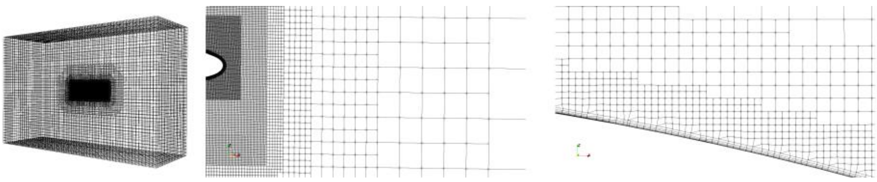

Figure 2. Hexahedral mesh

The inlet was modelled with a fixed value velocity of 28.5 m/s and a zero pressure gradient, while the outlet with a zero gradient velocity condition and a fixed value pressure. A slip condition was used for bottom, top and side.

The turbulence was modelled with *k-ω SST* model, setting the internal field to 1.52 $\times 10^{-4}$ m^2/s^2 for the turbulence kinetic energy k, 1042.03 s^{-1} for the rate of dissipation of the eddies ω and 1.46 $\times 10^{-7} m^2/s$ for the kinematic turbulence viscosity υ_t. In the simulation *kqRWallFunction* and *omegaWallFunction* boundary conditions were set respectively for k and ω.

The simulation was run for 2000 iterations, but *X'* reached a magnitude of 2.022 $\times 10^{-3}$ that is not significantly varying after 800 iterations. According to that, all the post-processing analysis were conducted on the results of the last of 800 iterations. The result obtained was compared against the average of the CFD results and the experimental result of "*NATO AVT-301 Collaborative Exercise: CFD Predictions for BB2 Generic Submarine, Phase 1 and 2 Comparison with Wind Tunnel Tests (2021)*".

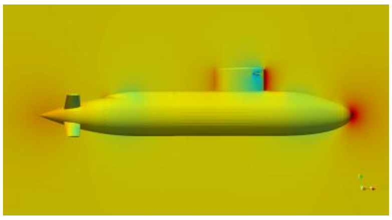

Figure 3. Simulation results of the pressure distribution

Table 2. Results comparison

NATO AVT-301 Collaborative Exercise		Present study result
Average CFD results	**Experimental result**	
1.87×10^{-3}	2.03×10^{-3}	2.02×10^{-3}

5. Case studies

In this paper several Case Studies were analyzed and, for each of them, the technology implemented and the theory that guided the choice of the hull modifications were presented.

5.1. Case Study 1 – Spherical sonar

The forward part of an underwater vehicle is always dedicated to the implementation of an active or passive sonar system useful to identify the presence of submerged or floating objects. Among all different configurations, a bow sonar in a spherical configuration allows to significantly increase the performances of the sonar system, that are also directly depending on the diameter of the array itself, but it is volume-demanding. In this case the shape of the bow was modified in order to increase the available volume for the sensor according to the space occupied from other systems in the bow. The vertical position of the sonar depends mainly on the primary role on the vehicle: for *Anti-Surface Warfare* (ASuW) vehicles an upward bow is preferable, while a downward bow is usually designed for *Anti-Submarine Warfare* (ASW) vehicles. In addition, the position of the sonar may also be influenced by the necessity to increase performances of other ship systems like introducing further torpedo tubes, emergency ballast tank blowing device, emergency bow thrust, high frequency sonar array, thrusts for *Dynamic Positioning System*.

Consequently two simulations were performed with two different geometries characterized by a different position of the end of bow compared to the original position (+/- 2 meters at full scale equal to +/- 2.849% of the length).

Figure 4. Configuration A: upward bow

Figure 5. Configuration B: downward bow

The respective results obtained were:

- 2.012×10^{-3} (-0.48%) for the *Configuration A*;
- 2.092×10^{-3} (+3.47%) for the *Configuration B*.

The analysis showed that a downward bow created a moderate increase in drag, more than upward configuration, due to the increased flow affecting the sail.

5.2. Case Study 2 – Sail position

According to the fact that the introduction of optronic periscopes gives more flexibility in the arrangement of the rooms on board, in this case the influence of different longitudinal positions of the sail were analyzed. Therefore, this modification may allow to choose the right position of the sail in order to improve the maneuvering characteristics of an underwater vehicle. As it is known, a sail placed at the *Pivot Point* reduces the attack angle during maneuvers in the horizontal plane and consequently the vortices and the *Snap Roll* thanks to a reduced side force. On the other hand, a sail placed at the *Neutral Point* allows to change the depth without changing the trim by operating the sail planes. A change of the position of the sail may also be required to reduce the turning radius or to carry on a payload in the external bow or stern part of the vehicle.

Consequently two simulations were performed with different geometries characterized by a sail placed forward and aft compared to the original position (+/- 5 meters at full scale equal to +/- 7.123% of the length).

Figure 6. Configuration C: forward-placed sail position

Figure 7. Configuration D: aft-placed sail position

The respective results obtained were:

- 2.031×10^{-3} (+0.43%) for the *Configuration C*;
- 2.033×10^{-3} (+0.55%) for the *Configuration D*.

The analysis showed that there were no important changes in drag due to different positions of the sail, so the introduction of optronic periscope may allow to choose the position of the sail in order to optimize other requirements like maneuverability and *Snap Roll*.

5.3. Case Study 3 – Blended sail

On modern submarines the trend to use the sail to accommodate a larger number of masts and *Special Forces* equipment has consequently meant an increase of the dimension of the sail compared to the size of the hull. In this scenario, it is important both to ensure a reduced magnitude of root-vortices, which may influence the flow into the propeller and the maneuvering in the horizontal plane, and to reduce *Snap Roll*. A blended type of sail is considered a valid solution, although, its larger volume compared to the foil type may increase the total drag, including wave resistance when operating near the surface, and decrease transversal stability during diving and surfacing.

Consequently, in this case, two different configurations better faired into the hull were developed.

Figure 8. Configuration E: blended sail

Figure 9. Configuration F: highly blended sail

The respective results obtained were:

- 2.038×10−3 (+0.77%) for *Configuration E*;
- 2.044×10−3 (+1.06%) for *Configuration F*.

The analysis showed that a blended sail, introduced a modest increase in drag, due to the increase in wet surface of the sail, but it is useful for reducing root-vortices and *Snap Roll*.

5.4. Case Study 4 – External payload

In order to improve for a limited period the global capability of an underwater vehicle, the implementation of external payload in the area behind the sail may often be a viable temporary solution. The payload may be a *Special Forces* vehicle, a hyperbaric chamber, a *Submarine Rescue Vehicle* (SRV), an AUV or a simple storage for containing a *Remotely Operated Vehicle* (ROV), an AUV or any special tools. Furthermore, a simple form with two different volumes was considered for representing an external payload. The smaller form was 10 meters long with a width of 2 meters at full scale, while the larger was 11 meters long with a width of 3 meters. In addition, for each payload form, a configuration with the payload integrated in the sail was considered in order to analyze the influence on the drag. In this configuration, an increase of the dimensions of the sail (25% for the length and 25% for the width respect to the original dimension) was considered to increase the residual volume of the sail.

Consequently, four different simulations were performed.

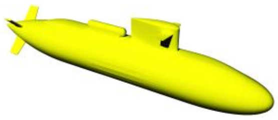

Figure 10. Configuration G: small payload

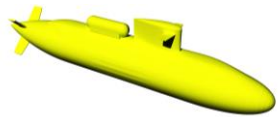

Figure 11. Configuration H: large payload

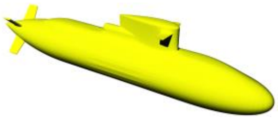

Figure 12. Configuration I: small integrated payload

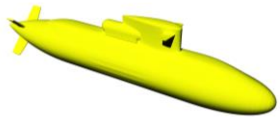

Figure 13. Configuration L: large integrated payload

The respective results obtained were:

- $2.322\times10{-}3$ (+14.82%) for the *Configuration G*;
- $2.755\times10{-}3$ (+36.26%) for the *Configuration H*;
- $2.247\times10{-}3$ (+11.10%) for the *Configuration I*;
- $2.452\times10{-}3$ (+21.24%) for the *Configuration L*.

The analysis showed that the integration of external payload into the sail significantly reduced drag compared to the configuration with the payload behind the sail.

5.5. Case Study 5 – Hexagonal section hull

In this case the influence of the introduction of a hexagonal section shape of the hull for reducing the target strength was evaluated.

Figure 14. Configuration M: hexagonal section hull

The results obtained was 2.133×10^{-3} (+5.46%) and it showed that a hexagon section form, for the reduction of target strength, introduced a moderate and acceptable increase in drag.

5.6. Case Study 6 – AUV and Midget Submarine form

In this case the influence of both the reduction of the dimension of the sail or the total absence on an AUV or a Midget Submarine was evaluated. A small sail (50% for the length respect to the original dimension) without foreplanes was realized to represent an external payload like a transducer, a GPS sensor, a CBNRE (chemical, biological, radiological, nuclear and explosive) sensor, a periscope camera or an AAV launcher.

While, a shape with no external payload is typical of vehicle that have high cruising speeds and do not have to interface with the atmosphere.

Consequently, two different simulations were performed.

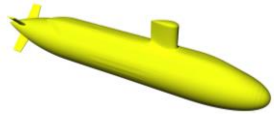
Figure 15. Configuration N: Small sail

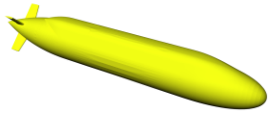
Figure 16. Configuration O: No sail

The respective results obtained were:

- 1.933×10^{-3} (-4.39%) for the *Configuration N*;
- 1.674×10^{-3} (-17.22%) for the *Configuration O.*

The analysis showed that the absence of external payload significantly reduced drag.

6. Conclusions

This study focused on the effect quantification of several modern technologies on the drag of a *Joubert BB2 Submarine* in 2 m model scale. The simulation environment was carried out considering that the flow is steady, turbulent and incompressible solving the RANS equations with a *k-ω SST* turbulence model and was validated by comparing the result with the CFD and the experimental data reported in the "*NATO AVT-301 Collaborative Exercise: CFD Predictions for BB2 Generic Submarine, Phase 1 and 2*".

Furthermore, thanks to the results of additional Case Studies, it was possible to identify the optimized shape solutions for the implementation of different modern technologies, related to the underwater sector, on Submarines or AUVs.

In conclusion, the outcomes achieved showed how the *Platform and Security Office* of the *Submarines Department* of the *Italian Navy General Staff* built up its own capability to estimate the drag of underwater vehicles. The capability, implemented using *open-source* software and an already available computer, will allow to conduct CFD studies on in-service Submarines, interested by significant design modifications, and on the future concept designs including the *Next Generation Submarine* related to the *Future Combat Naval System 2035 Program* of the *Italian Navy*.

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