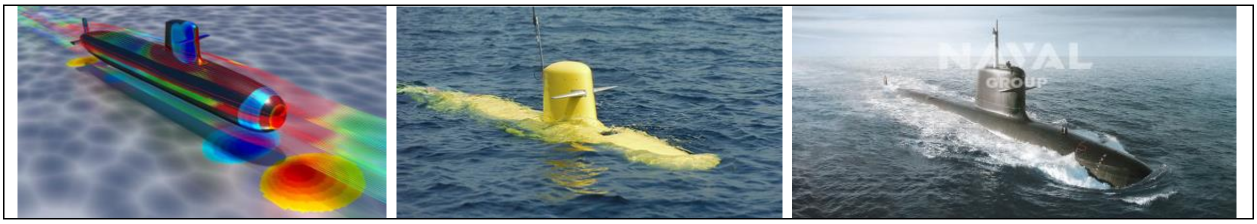
Shallow and infinite water manoeuvring of submarine: integration of Computational Fluid Dynamics (CFD) in the design process

F. Pétillon[1] (francois.petillon@naval-group.com), L. Bordier[2], F. Dauce[1], JJ. Maisonneuve[2], A.Nédellec[1], C. Yvin[2]

[1] Warship Performance Department, Naval Group, France
[2] Naval Platform Modelling Department, Sirehna, France



SUMMARY

The design of ship external shape, consistent with both architectural constraints and manoeuvring performances requirements, is crucial for the submarine projects at Naval Group. The deployment of numerical methods for hydrodynamics, in infinite water as well as in constrained and shallow water, represented a revolution in the historical design process. For several years, these methods are systematically applied to new projects of submarines.

Although numerical simulation has already been used for several decades in submarine design, Naval Group is investing on these new calculation methods for almost 10 years. By their mean, main performances of the submerged submarine like dynamic stability, turning diameter, trim change capability, forces coefficients for elementary motions (forward speed with drift/incidence, rudder angle…) and appendage hydrodynamic loading become predictable.

For infinite water calculations, the validation of these methods is made upon the accumulated knowledge on the different submarine designed, built and sea-proven by Naval Group during the last five decades. The turning performances are thus compared to the results from sea trials of the studied submarines. The efforts on the submarine and the hydrodynamic loads applied to the rudders during elementary manoeuvres are compared to model tests measurements. This comparison on an extensive database enabled to validate the deployed methods, and to quantify the inherent uncertainty.

In modern submarine warfare, operations in coastal and shallow areas are becoming more frequent and more demanding. For the design process, this requires performance prediction tools that are adapted to take into account the hydrodynamic interaction with the seafloor.

1. THE INTEGRATION OF CFD WITHIN SUBMARINE DESIGN PROCESS

1.1. Submarine design and manoeuvrability

Submarine manoeuvring capability represents a crucial stake for submarine projects, from the early design stage to the real condition exploitation at sea. The implications of manoeuvring capability on a submarine project are the following:

- Operational capability (turning capability, diving capability, controllability)
- Navigation safety (submarine behaviour in case of hydroplane failure or flooding)
- Control surfaces and actuator design (structural design to withstand hydrodynamic forces, capacity of the actuators)

Therefore, the hydrodynamic characteristics of the submarine have to be designed carefully, taking into account the associated constraints and requirements.

Within the submarine design process, the hydrodynamic studies are conducted with several objectives. A first aim is to evaluate the impact of design constraints and requirements on external forms of the submarine. A second purpose is to assess the compliance of the submarine design with its required capabilities. A third aim is to ensure that the risk associated with the submarine design remains under control, and consistent with the allowable risk level for the considered design stage (pre-project, basic design, detailed design).

1.2. Standard process for manoeuvrability studies

The standard process for hydrodynamics studies can be divided in two different parts:

- Design definition for systems and architecture
- Performances assessment of the defined design

The main driver for both part is the requirements objectives, whether it is performance objectives (for example: turning diameter objective) or architectural constraints (for example: choice of X shaped hydroplanes).

Design definition takes into account the external constraints, through the interactions between the hydrodynamic studies and the other parts of the submarine design process. The performance assessment is made through analysis of the defined design, and based upon dedicated manoeuvring performance evaluation studies.

The overall process is described in the following picture:

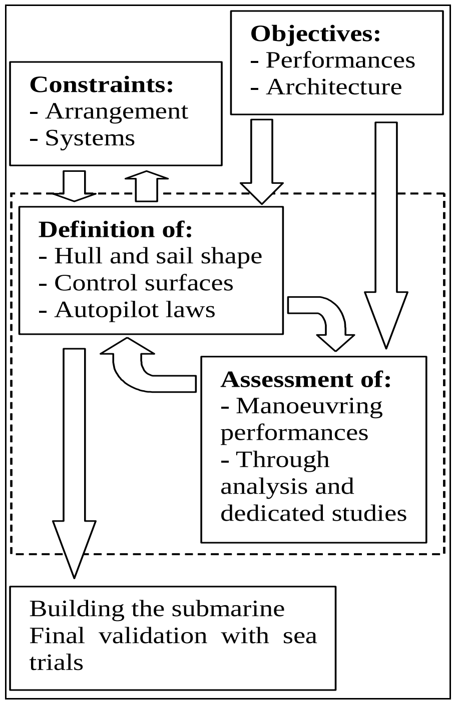


Figure 1: Hydrodynamics studies and interaction with submarine design process

The correct integration of the hydrodynamic studies within the design process, in terms of planning and risks, depends on the availability of suitable tools for performance assessment.

1.3. Standard tools for manoeuvrability performances assessment

1.3.1. Hydrodynamics toolbox

Different tools can be used in hydrodynamic studies for performances evaluations. A brief summary of the different tools used at Naval Group is presented in this part.

Preliminary tools:

Analysis based on feedback from previous submarine, empirical formulas. Tool used for:

- First assessment of manoeuvrability coefficients
- Use of simulations to get preliminary assessment of submarine performance

Computation Fluid Dynamics:

CFD computation of free running performance. Tool used for evaluation at deep diving depth of:

- Dynamic stability
- Turning radius
- Ability to change trim
- Forces on rudders and hydroplanes

It is important to note that where previous numerical calculations were generally used for relative analysis, the new CFD methods are now used for quantitative evaluation purposes.

Free running physical model:

Re-configurable free running manoeuvrability model (cf. [2]).

Tool used for evaluation at deep diving depth of:

- Dynamic stability
- Turning radius
- Ability to change trim
- Forces on rudders and hydroplanes

Tool used for evaluation on surface of:

- Turning radius

Complementary tools:

Specific CFD computation and model tests, for dedicated analysis and/or mathematical manoeuvring model definition.

CFD used for:

- Determination of linear manoeuvrability coefficients

Model test used for:

- Determination of non-linear manoeuvrability coefficients

1.3.2. Integration within submarine design process

Depending of the context of the design phase (pre-project, design definition …), these tools are integrated in the hydrodynamics studies.

The process for a typical design phase is represented on Figure 2 below. Design definition as well as performance assessment are displayed, as presented in part 1.2, continuously interacting. This process takes into account the different manoeuvrability requirements, including shallow water navigation.

The previously described tools are used following a specific strategy, depending on the phase duration and the risk allowance for performance knowledge.

At the early stage of a project, fast iterations are conducted using preliminary tools, then CFD evaluation on the defined configurations.

To lower the risk associated with high value performance, and adjust submarine design consequently, specific verification can be made using a free running model.

For the more advanced phases, when no more major design iteration is needed, extensive knowledge of submarine behaviour can be obtained through complementary model test and CFD calculation.

On figure 2, the time factor is not pictured on a representative scale. This is however a key parameter for the tools utilisation strategy: for the more advanced tools (for example model tests), design evolution can happen faster than evaluation results.

In such cases, the tests results are therefore obtained for an out of date design configuration. The consistency between the design definition and the performances evaluation is then ensured through an analysis of the impact of design changes on performances conducted all along the phase, based on preliminary tools and/or CFD when necessary, until the final configuration is tested.

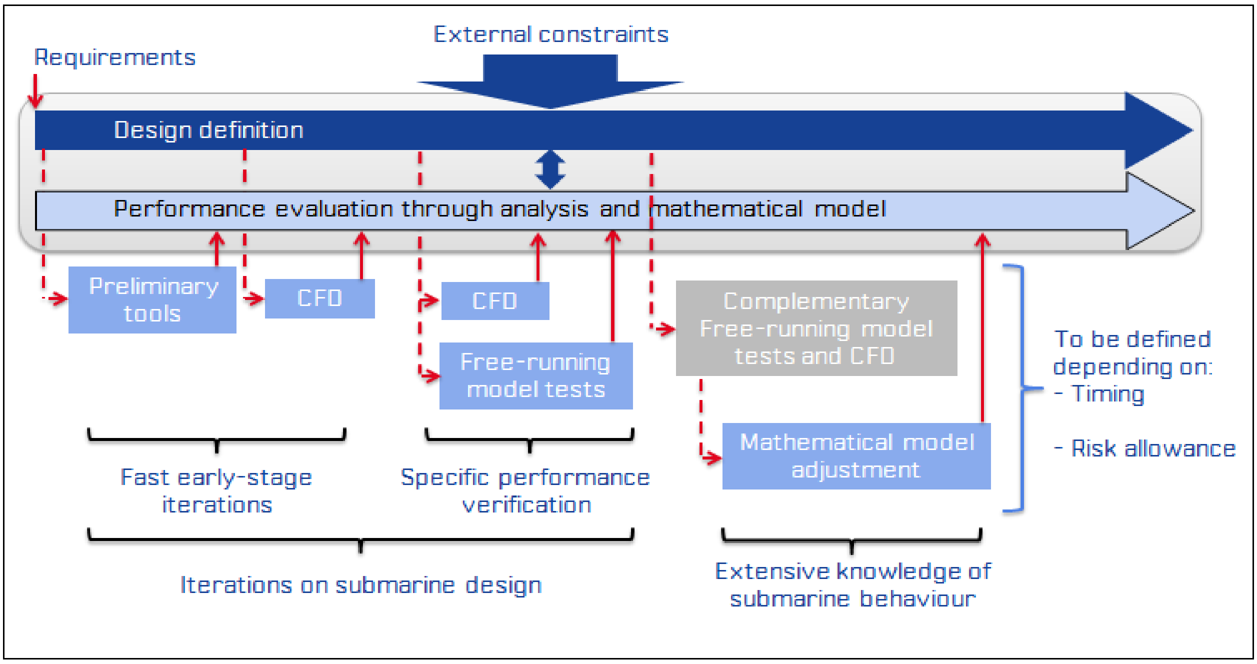


Figure 2: Representation of deployment strategy of manoeuvring performances tools during a standard design phase

2. CFD BASED METHODS FOR MANOEUVRING PERFORMANCES EVALUATION

2.1. Approach

The objective is to build a calculation process that is fully qualified against reference data, reliable and efficiently applicable to the design needs. Although numerical fluid dynamics computation were already used before this work, in particular in a relative way, the ability to ensure a low absolute uncertainty level represents a step forward.

The first stage is to define a calculation setup which leads to converged and accurate results: grid rules, methods for motions modelling, numerical parameters for the flow resolution, post-processing methods.

The second stage is to ensure that this setup is convenient to the whole range of reference test cases, and iterate as necessary toward this objective, so that the method can be considered as valid for new cases of the same type.

Once this is done, the last stage consists in embedding the rules and methods into an automated process, associated with tools for a fast verification of results, in order to get an error-less process that can be applied with confidence, whoever the operator, and at the lowest possible cost.

All these stages were conducted. Only the first and second stages are described hereafter.

2.2. Fluid Solver

The fluid solver used for the simulation of external hydrodynamics around submarines is STAR-CCM+. This is a generic multi-purpose CFD solver originally developed and distributed by CD-Adapco, and now part of Siemens PLM Software engineering suite. This is a finite volume based solver running with an unstructured mesh composed of arbitrary shaped cells (hexaedra dominant or polyhedra). Steady or unsteady flow can be solved by means of a coupled solver or a segregated solver using predictor / corrector algorithm to couple pressure and velocity (SIMPLE like algorithm). Reynolds average Navier-Stokes equations can be solved with different turbulence models like k-epsilon or k-omega SST. Alternatively, large eddies can be solved by LES or hybrid RANS-LES methods.

The required features of the CFD code for submarine simulations in manoeuvrability conditions were:

- the ability to handle free moving objects,

- the ability to easily iterate on multiple designs by replacing some parts of the submarine without too much engineering effort (automatic meshing process),

- the ability to increase simulation speed, allowing necessary refinement to increase accuracy when necessary (combination of scalability and flexible licensing with regard to number of cores used).

2.3. Meshing

Meshing of the domain is done with STAR-CCM+ internal meshing tools. Various possibilities exist in STAR-CCM+ to mesh the external domain of the submarine (Tetrahedral, Polyhedral, Hex-dominant trimmer). Because the flow has a principal direction in most cases (submarine with moderate drift angles), the hex dominant mesher is preferred. The method is called Trimmer in STAR-CCM+ and is based on a Cartesian hex template, refined in the proximity of the body surface by cutting each hex cell in smaller hexes to meet curvature criteria or an user defined refinement size. In the proximity of the surface hexes are cut to have good projection to the surface, giving polyhedral cells when necessary. Then a boundary layer extrusion can be added to have a mesh suitable for a high range of Reynolds numbers.

An iterative procedure for the verification of mesh discretisation error is used to find mesh size and refinements suitable for computing submarine manoeuvrability in an accurate way. Table 1 and figure 3 are an example of a mesh sensitivity study in captive pure horizontal rotation with a base mesh and 2 successive mesh refinements on the forebody. The effect of refinement does not exceed 1% in this case. Other mesh refinements are compared in this way, like mesh size near sail, effect of y+ or layer progression ratio… A last sensitivity study considers the effect of flow based refinements. Table 2 and figure 4 summarize verifications made by refining with a vorticity based criteria. In this case, variations in forces and moments increase up to 2.5%.

The final meshing procedure is then based on the different mesh sensitivity studies.

	Cx (-)	Cy (-)	Cn (-)
Mesh 1, 27M	1.0000	1.0000	1.0000
Mesh 2, 29M	0.9960	1.0000	1.0038
Mesh 3, 51M	0.9944	0.9994	1.0077

Table 1: Forebody mesh influence on submarine force coefficients, non-dimensional values

	Cx (-)	Cy (-)	Cn (-)
Mesh 1, 27M	1.0000	1.0000	1.0000
Mesh 4, 30M	0.9929	1.0008	0.9923
Mesh 5, 84M	0.9833	1.0018	0.9770

Table 2: Effect of mesh refinement with vorticity field criteria, non-dimensional values

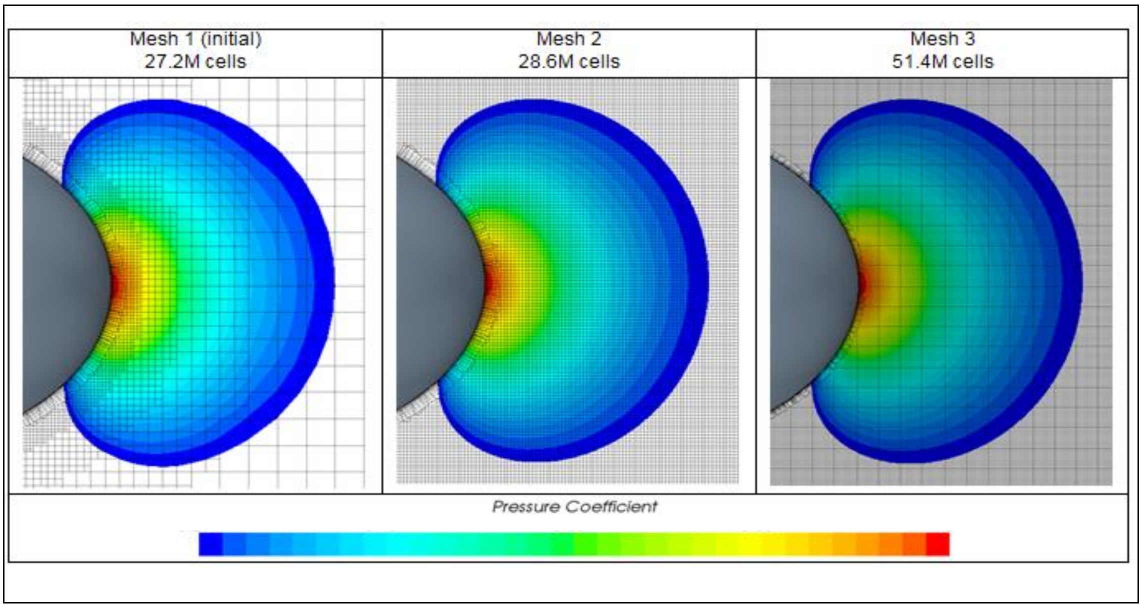


Figure 3: Mesh influence on submarine forebody Pressure Coefficient

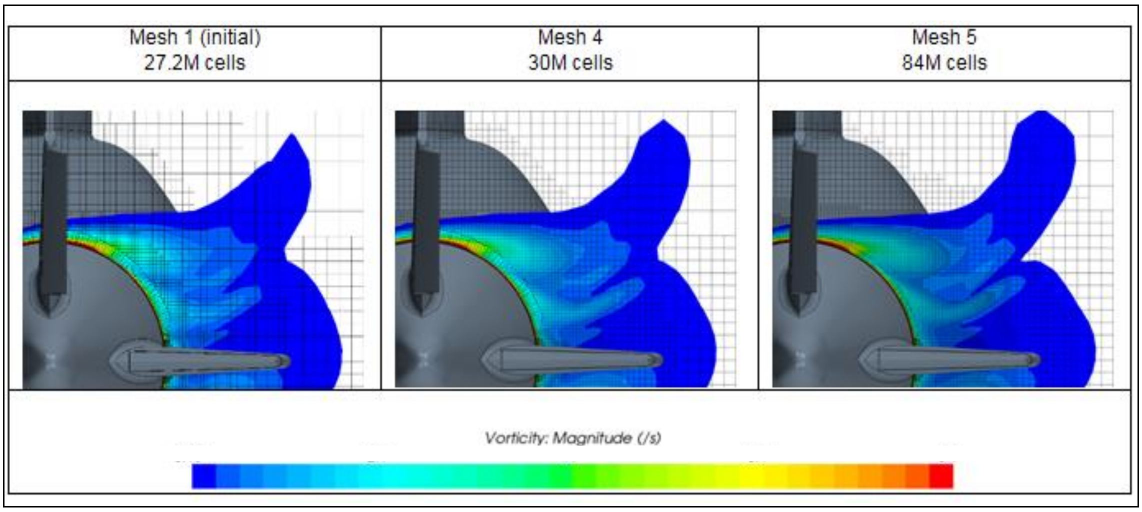


Figure 4: Mesh refinement based on vorticity criteria, in high drift gyration

2.4. Captive simulation modelling

Captive simulations are necessary to obtain the mathematical manoeuvrability model of the submarine, i.e. forces derivatives with respect to elementary motions of the submarine or appendages. These coefficients are usually obtained by means of captive model tests. With simulation, a similar approach is used.

This assessment of linear coefficients (see [1] for definition of coefficients) requires the following calculations conditions:

- straight course (no drift and no incidence, no rudder angle): this gives the resistance of the submarine and the offline forces coefficients C_{z0} and C_{m0}
- static drift to compute C_{yv} and C_{nv}
- static incidence to compute C_{zw} and C_{mw}
- rudder and hydroplane angle variations to compute $C_{z\beta1}$ | $C_{m\beta1}$ and $C_{y\alpha}$ | $C_{n\alpha}$, $C_{z\beta2}$ | $C_{m\beta2}$ for + arrangement hydroplanes and rudders
- steady horizontal turn (without drift) to compute C_{yr} and C_{nr}
- steady vertical turn (without incidence) to compute C_{zq}, C_{mq}

The simulation parameters for these conditions are mostly classical, the submarine is considered in a fixed position with velocity inlet condition on the upstream boundary and pressure outlet condition on the downstream boundary. Meshing is probably the most critical difficulty, and refinements are done based on the sensitivity studies as presented before. One valuable procedure applied here is to align the Cartesian template on the main direction of the flow, and thus, the mesh is updated for each condition in this objective. Wall functions are used to avoid solving the viscous sublayer which would require too many points at real scale for the available computation resources. Nevertheless, a high number of viscous layers is needed to solve the boundary layer correctly.

For static drift and static incidence, the variations are applied by changing the velocity condition on the inlet boundaries. For rudder angle variations, only the rudder angle is changed in the geometry, then the mesh is automatically updated without any engineer resource needed. For steady turn in the horizontal and vertical planes, the Navier-Stokes equations are solved in a rotating reference frame to account for flow rotation.

In addition to the global forces coefficients the rudder angle variations also give an assessment of lift, drag and torque at rudder stock.

Samples of results obtained for captive conditions are given in section § 3.2 with an estimation of the differences to experiments.

2.5. Description of free running simulations

Free running simulations are a step beyond in complexity since the movement of the submarine submitted to fluid and external forces (like propeller force) has to be solved at the same time.

Four types of free running simulation are usually performed and have been compared to real submarine at sea.

2.5.1. Horizontal turning with 0° rudder angle

The first type of simulation concerns horizontal turning rate with 0° rudder angle, to assess the ability of the submarine to keep a straight course after a small perturbation. The simulation set up for this condition is to have the submarine free to move in the horizontal plane, after a first forced straight ahead course giving its propulsion force. Then a disturbing yaw moment is applied for a short time to initiate a change of direction, and is then cancelled. The following calculated trajectory allows assessing the degree of horizontal dynamic stability of the submarine. By this simulation process, the designer can see the direct effect of rudder / sail design on the stability of the submarine before assessing the full manoeuvring operating conditions.

2.5.2. Vertical stability with 0° hydroplane angle

The vertical dynamic stability requires a similar type of simulation. The objective here is only to assess the dynamic stability characteristic of the shape, through an evaluation of the trim evolution rate at 0° hydroplane angle. For this purpose, the simulation ignores the hydrostatic restoring moment and also cancels the vertical plane asymmetric forces (C_{z0} and C_{m0}).

2.5.3. Steady turning rate in horizontal plane with rudder

The steady turn in horizontal plane is the next type of simulation to be presented. The submarine is still in free running condition for the horizontal plane and its propeller force.

Figure 5 gives the circular trajectory of the submarine. Figures 4 and 6 illustrate the complex flow in the wake of a submarine in steady turn, with a high vorticity wake coming from separation from the hull and from the rudders.

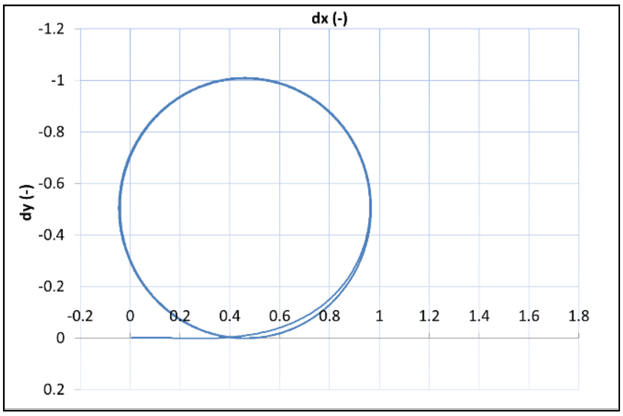


Figure 5: Free run turning condition – trajectory

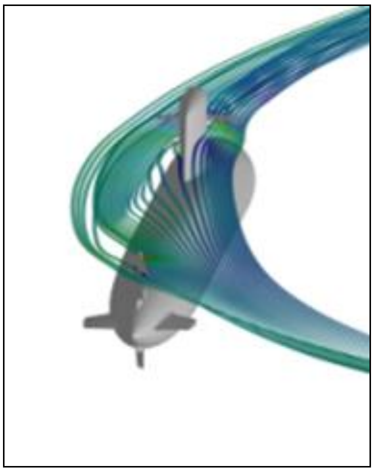


Figure 6: Flow lines in wake of submarine during steady turn

2.5.4. Trim change

The last type of free running simulation is a change of trim. Unlike the vertical stability, a permanent state results from both hydrodynamic and buoyancy forces and moments.

Figure 7 gives an example of trajectory computed in the free running simulation, and figure 8 shows the convergence in trim.

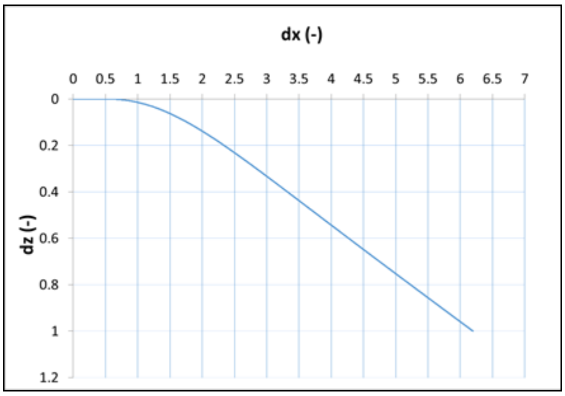


Figure 7: Free run change in trim – trajectory (arbitrary coefficient)

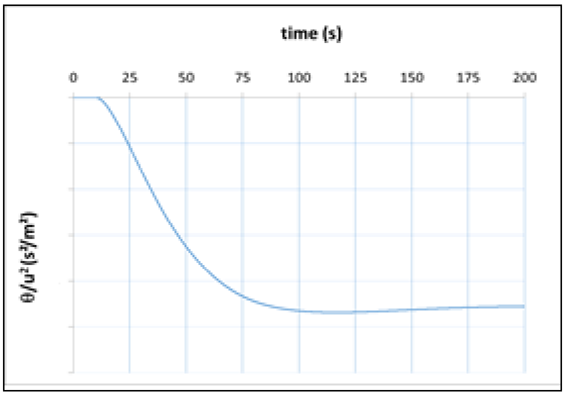


Figure 8: Free run change in trim – trim convergence

3. VALIDATION OF CFD METHODS – INFINITE DEPTH

3.1. Validation Cases

The use of Computational Fluid Dynamics (CFD) in the design process of submarines requires knowing the level of confidence of such methods. When submarine architects and hydrodynamics engineers are designing new shapes, different tools are used to assess the performance of the design. As each tool (simulator or physical model) has its own uncertainty, the cross validation of all the results and uncertainties of the whole toolset give the designer a better confidence in the assessment of the performance of the new project.

A decade ago, CFD calculations were already widely used in the domain of manoeuvrability, mainly for comparison purposes. An important investment has been decided in hardware and manpower to bring the simulation process into a quantitative assessment tool in the domain of manoeuvrability. Many publications in the literature mentioned CFD validation on academic shapes (like 6:1 ellipsoid [10]) or submarine shape like SUBOFF or Joubert Australian shapes [4], [7]. Despite the interesting nature of these validation cases regarding to fluid physics and CFD modelling, there was a strong motivation in Naval Group to assess the simulation bias compared to real scale sea data.

The choice was thus made to use the existing information on real submarines at Naval Group for validating the CFD simulation process. The CFD method had to be validated for all submarine appendages and propeller type.

The reference data consist of hydrodynamic performance of existing, sea-proven submarines. To have enough confidence in the results, a base validation set was made of different submarines, designed from 1960, including SSKs, SSNs and SSBNs.

Different types of data are then used in the process of numerical methods validation in infinite depth:

- A first validation data set comes from the sea trials records for the base validation set submarines.
- A second set of data comes from model tests.

The origin of the reference validation result depends on the considered characteristics:

- For manoeuvring performances, the values determined from the submarines sea trials are considered as validation data for CFD. For newest submarines, for which sea trial data are not available yet, large scale free running model data are taken into account.
- For the evaluation of forces on rudders and linear manoeuvring coefficients, model scale captive model tests results are considered as validation data for CFD.

3.2. Results for captive simulations

As a first step to CFD validation, simulations are compared to experiments in towing tank. The validation process includes 6 main submarines.

The following figures give some comparisons between CFD and model tests.

As illustrated by figures 9 and 10, the drift coefficients C_{yv} and C_{nv} are very close to the experiments when computed with CFD.

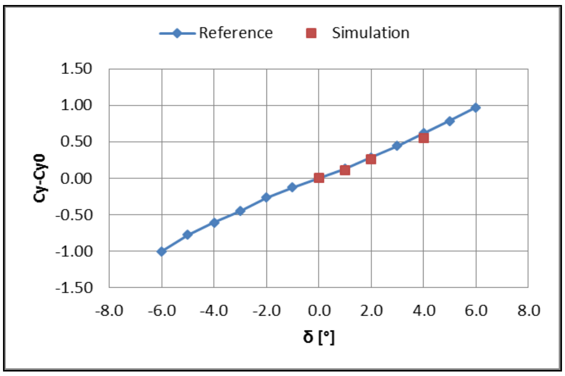


Figure 9: Drift Y force coefficient (arbitrary value coefficients)

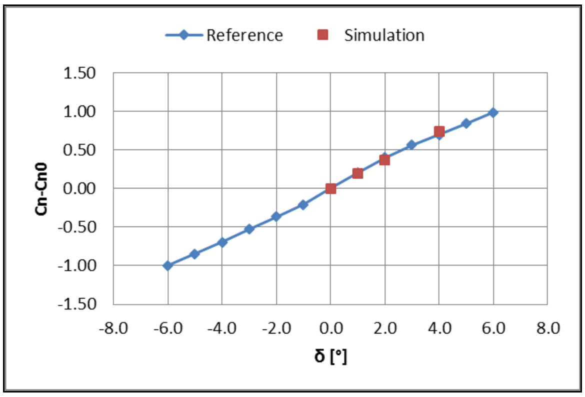


Figure 10: Drift Z moment coefficient (arbitrary value coefficients)

The rudder effectiveness is also well assessed by CFD simulations as presented in figures 11 and 12 for stern hydroplane.

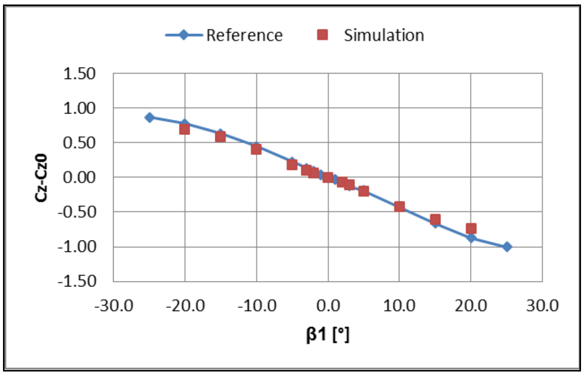


Figure 11: Hydroplane efficiency– Z force (arbitrary value coefficients)

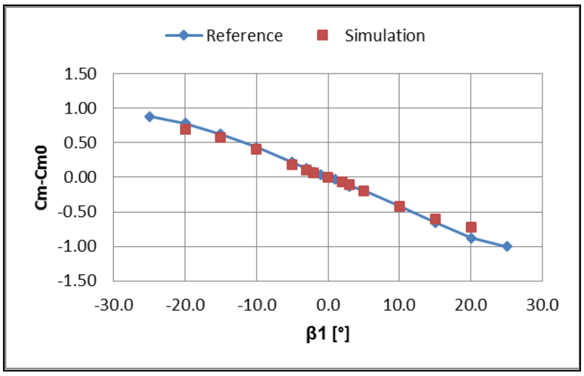


Figure 12: Hydroplane efficiency– Y moment (arbitrary value coefficients)

Steady turn simulations are the more difficult conditions since the flow physics is much more complex, with separation and curvature / rotation effects. Nevertheless, pure rotation simulations give satisfactory results as shown in figures 13 and 14.

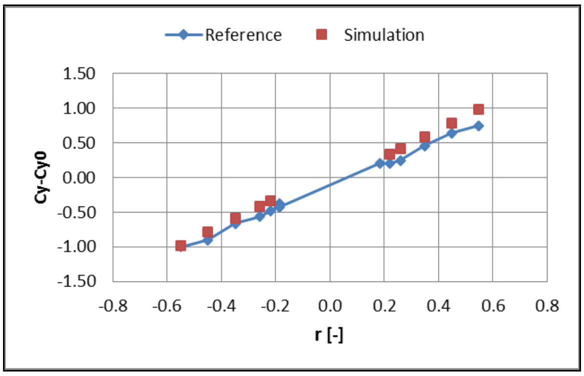


Figure 13: Pure horizontal rotation – Y force (arbitrary value coefficients)

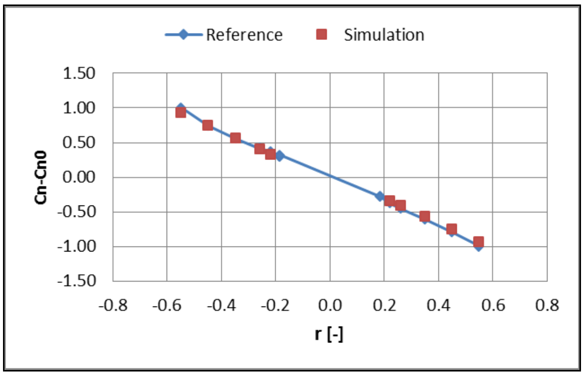


Figure 14: Pure horizontal rotation – Z moment (arbitrary value coefficients)

Similarly to the horizontal plane, the pure rotation in vertical plane is shown in figures 15 and 16.

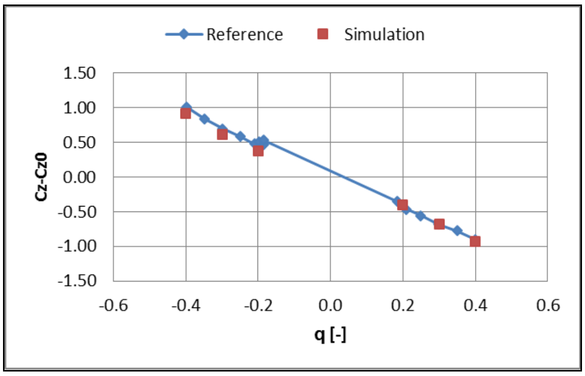


Figure 15: Pure vertical rotation – Z force (arbitrary value coefficients)

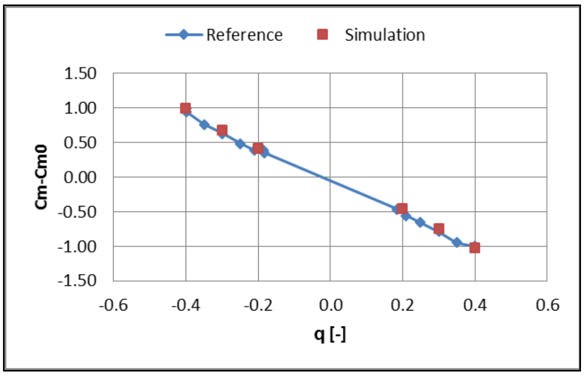


Figure 16: Pure vertical rotation – Y moment (arbitrary value coefficients)

CFD simulations are also used to give preliminary estimations of the needed rudder actuator power, through the rudder stock torque. In figure 17, the calculated torque coefficient is compared to model experiments.

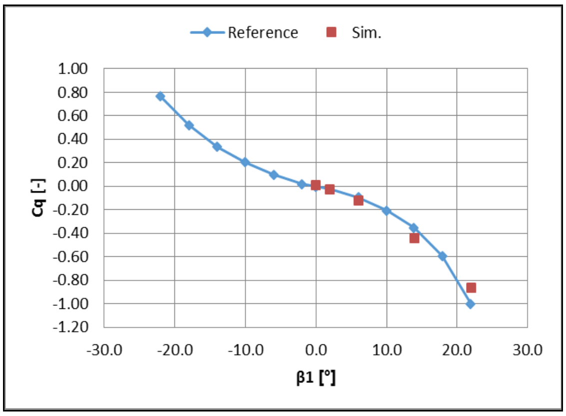


Figure 17: Stock torque assessment (arbitrary value coefficients)

3.3. Results for free running simulations

Turning rate in infinite depth with extreme rudder angle were computed for 3 submarines, and compared to the sea trials results. This procedure confirms the validity of the CFD simulation in free running and real scale conditions. The comparison presented in figure 18 gives an assessment of the main manoeuvring characteristic (turning radius) with less than 5% difference from sea trials.

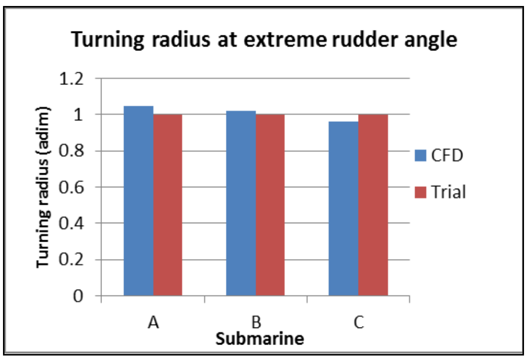


Figure 18: Turning radius at extreme rudder angle, comparison between CFD and trials (arbitrary value coefficients)

These results compared with sea-proven submarines give the designer the ability to study different hull shapes and appendages. By taking into consideration a margin associated to the validation of the CFD process, the manoeuvrability performance can be estimated correctly before first experiments in free running model tests.

4. CONSTRAINED AND SHALLOW WATER SPECIFICITIES

4.1. Context and operational needs

A submarine mission is rarely limited to oceanic operations. For most navies, being able to conduct Special Forces and information missions on coastal areas is a necessity. And for some of them, their geographical operation zone is mostly made of restrained depth areas, such as the Baltic Sea or the Timor Sea. Thus, the ability to operate in constrained and shallow water (CSW) has to be included in the various abilities of the submarine.

In infinite water conditions, there is no limit for submarine navigation, except the sea surface and the submarine own capacity. By definition, the submarine is considered in CSW condition when the sea depth is less than the submarine maximum operating depth. In such conditions, additional navigation constraints must be taken into account. In particular, navigation situations in which the submarine is close to both sea bottom and sea surface must be considered.

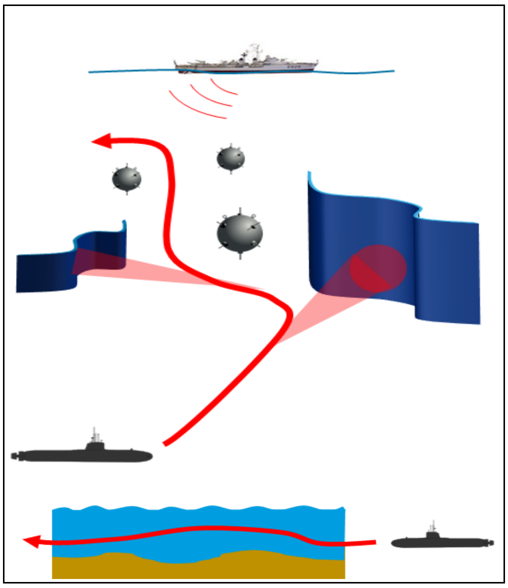


Figure 19: Navigation constraints in shallow water

CSW conditions have two main impacts on the submarine design. The first one is a need of excellent manoeuvring capability, and a perfect knowledge of the submarine behaviour from the early stages of design. This is necessary to ensure accurate navigation path, obstacle avoidance, and submarine capability to counter external perturbations with a strong tolerance precision. Such external perturbations can have different types: waves effect, changes in water density or in submarine weight... The aim is to be able to size correctly the different actuators, and to optimize accordingly the submarine autopilot for such applications. For this purpose, the manoeuvring capability needs not only to be good but also to be predicted with enough accuracy from the early design stage to the sea trials.

The second impact is the need of additional safety analysis, to ensure safe submarine recovery in case of a failure (for example, hydroplane jam or flooding). The behaviour of the submarine in such cases is assessed, and additional manoeuvring limitations and margin to the seafloor are implemented, depending on the evaluation result. To conduct this analysis, a perfect knowledge of the submarine behaviour, and of the CSW specific effects, is also needed.

4.2. CSW specific phenomena

Apart from the presence of additional obstacles, several supplementary effects linked with restricted water must be taken into account when addressing shallow water navigation.

A first type is the effect generated by the proximity of the sea surface: waves effect and self-generated waves with submarine advance speed. Such effects are already studied and known for long, as they are crucial for oceanic submarines, when operating close to the sea surface.

A second type is the effect of hydrodynamic interaction with the sea bottom: close to an obstacle, the hydrodynamic flow around the submarine is modified, thus inducing a modification on the hydrodynamic forces exerted on it. The main effects are an apparent increase of the ship inertia ("added mass effect") and an apparent suction effort, pulling the submarine closer to the sea bed.

Such a phenomenon is well known for surface ships: for example, a suction effect is observed when navigating in a canal.

4.3. CSW hydrodynamic studies in design process

As described in part 1, manoeuvring capabilities of the submarine in CSW are studied within the design process. The same tools as for infinite water manoeuvrability can be used, although their application range is different.

Model tests in shallow water are possible, and were already conducted on submarine projects: free running model in lake close to the lake floor, and captive and free running model tests in towing tank, close to the bottom. However, such tests are long and complex: beside the length and complexity of the test itself, the analysis of shallow water effects requires an accurate measurement of submarine motions, forces and under keel clearance. Because of this complexity, they do not allow optimising and verifying performance on the whole range of operational scenarios.

Nowadays, Computational Fluid Dynamics (CFD) is widely used by Naval Group for manoeuvring performance prediction (as presented in part 2), in infinite water as well as in shallow water.

With a Reynolds Averaged Navier-Stokes (RANS) solver, steady state and non-stationary calculations are made. With steady state calculation, forces on the submarine body and appendages are calculated, including the forces linked to the presence of a close sea bottom. With non-stationary calculations, direct manoeuvring characteristics such as turning diameter are assessed. The effect of a sea floor, flat or not, can be taken into account. Compared to model tests, such CFD methods can be used on a wider range of configurations, with a reduced time and cost.

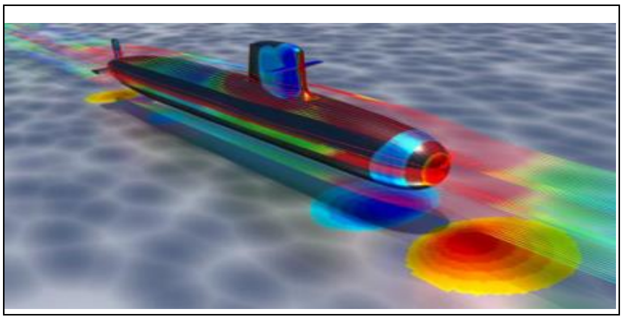


Figure 20: CFD calculation in shallow water

For several applications, CFD and model tests must be completed with the use of lighter tools to address the following needs:

- Parametric studies on a wide range of configurations
- Optimisation of submarine design and autopilot
- Analysis of the submarine behaviour in complete scenarios

In such cases, the submarine motions are obtained from the integration of motions equations, including external hydrodynamic forces exerted on the submarine. Such a method is systematically used for manoeuvring prediction in infinite water, and can take into account additional external or internal forces. During the past decade, Naval Group improved this calculation method to better take into account CSW effects. The CFD calculation of the additional forces to be taken into account with this approach is presented in the next part.

4.4. CFD input data for CSW Manoeuvring performance prediction

4.4.1. Ship motion modelling

The manoeuvring performance prediction tool used by Naval Group is based on the numerical solving of Newton's second law, as described above. The different external forces exerted on the submarine are modelled in this tool, including the interactions with sea bottom and sea surface.

To model the interaction effect of a flat sea bottom, it is useful to define the clearance between the submarine mean keel line and the sea bottom, cf. figure 21:

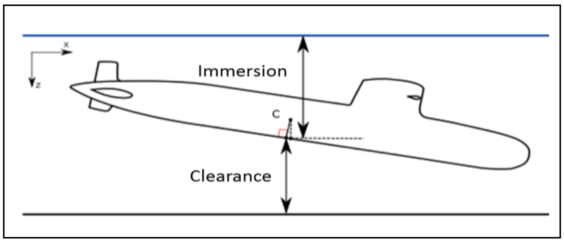


Figure 21: Convention definition for clearance between submarine and sea bottom

The additional forces can be separated in three different types:

- Additional forces proportional to the submarine acceleration : added mass effect
- Vertical force, proportional to the square of submarine speed : suction effect
- Modification of the hydrodynamic pitching moment.

The effect on added mass is already treated in the open literature (for example [13]). The calculation method used for the vertical force and the pitching moment is detailed in the next part.

4.4.2. Evaluation of additional vertical forces

When the submarine navigates close to the sea bed, it is subject to a downward vertical force. This suction effect is caused by the acceleration of the flow between the submarine hull and the sea bed. This acceleration causes a pressure decrease, determined by the Bernoulli law.

Because this suction effect is mainly due to a pressure distribution modification, the fluid viscosity has little effect in this phenomenon. Therefore, it is relevant to assess it with the perfect fluid hypothesis. With such an hypothesis, the fluid viscosity is neglected and the forces generated on the submarine can be solved analytically with Boundary Element Method (BEM) software. BEM software is easier and faster to use than RANS calculation, the computation time being generally less than a minute, which is interesting for preliminary optimisation studies.

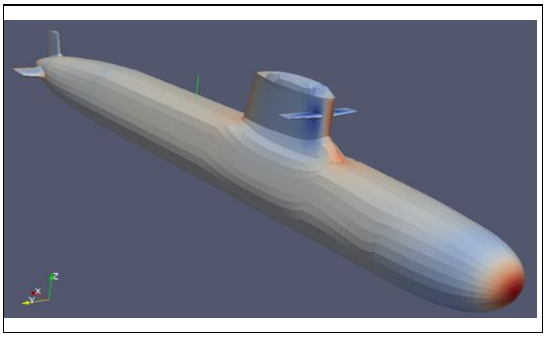


Figure 22: Example of Boundary Element Method (BEM) calculation result

The BEM software used by Naval Group for this application is REVA. To validate the use of this software for CSW suction effect computation, BEM calculations were compared to RANS calculations on a submarine shape. The comparison is presented in figure 23, showing a rather good correlation.

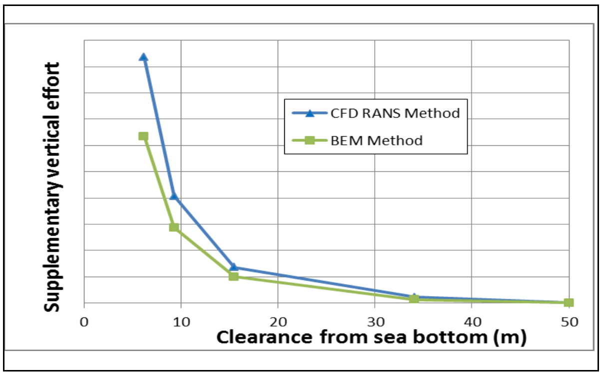


Figure 23: Vertical effort close to a sea bottom – comparison between RANS and BEM methods

In addition to this validation, the results obtained with Naval Group method were compared to results from the literature (references [11] and [12]). In these studies, the considered submarine is not the same: for comparison purposes, the results are extrapolated to an equivalent submarine size and speed.

Because the studied submarines shape is not identical for the different studies, there is some dispersion in the value results. However, the order of magnitude of the effort is equivalent for the three studies. This comparison work confirms that Naval Group BEM method is able to give a quick and good evaluation of the vertical force due to submarine-ground interaction.

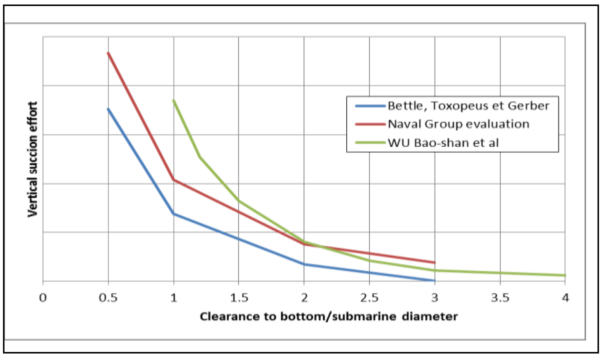


Figure 24: Vertical force close to a sea bottom – comparison between Naval Group results and literature results

4.4.3. Evaluation of additional pitching moment

In CSW conditions, the submarine can be subject to a modification of the pitching moment. The physical phenomenon is the same as described in part 4.4.2. However, the pitching moment is strongly influenced by the flow modification around the aft hydroplanes. The figure 25 shows the pitching moment close to the sea floor obtained with RANS calculation, with and without aft hydroplanes. This illustrates the impact of aft hydroplanes on the pitching moment.

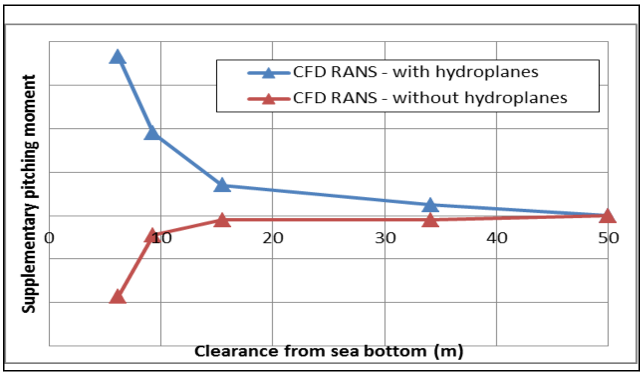


Figure 25: Pitching moment close to sea floor with and without aft hydroplanes – RANS calculations

It is commonly agreed that without any correction, BEM methods are not adapted to evaluate efforts on a lifting surface. Therefore, to evaluate correctly the pitching efforts with BEM calculation, a correction must be made to take into account the lifting effects on aft hydroplane. The figure 26 shows the comparison between RANS, BEM without and with correction on the pitching moment.

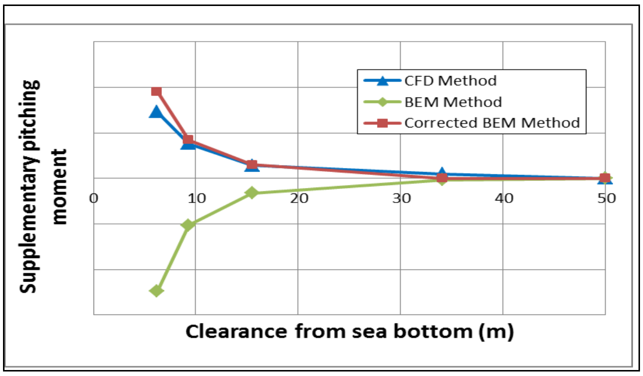


Figure 26: Pitching moment close to sea floor – comparison between RANS, BEM and corrected BEM

The pitching moment evolution with the submarine trim was also studied. The comparison is presented in figure 27:

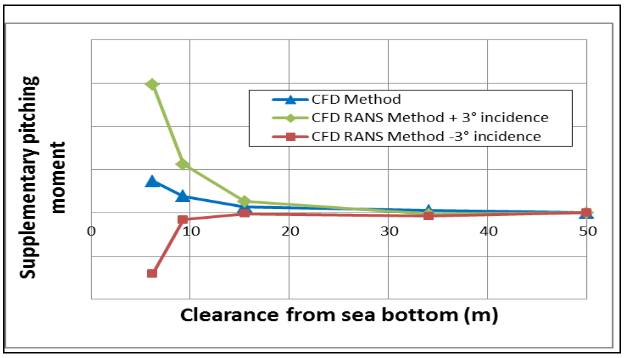


Figure 27: Pitching moment close to sea bed –trim variation effect

Finally, a comparison between the results at 0° trim angle and literature data was made, with the same extrapolation method for the comparison on different submarine shape as in part 4.4.2. The comparison is presented in figure 28.

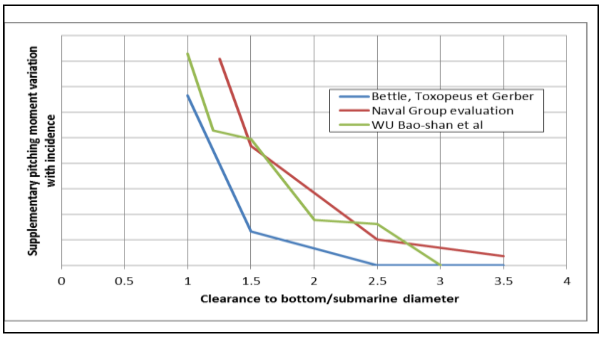


Figure 28: Pitching moment close to a sea bottom – comparison between Naval Group results and literature results

As a conclusion, the work presented in this part shows that for CSW pitching moment evaluation, RANS calculation or BEM method with correction taking into account lifting surfaces gives a correct estimate. This also shows that the supplementary pitching moment is influenced by the submarine trim.

Finally, for specific time domain simulations, effects of the sea floor are well estimated either by complete RANS calculations or for quick and preliminary optimisation by adapted BEM calculations.

5. CONCLUSION

The current process for submarine manoeuvrability assessment in the design phase is described in this article. In this process, the CFD based approach plays a crucial part, as it allows a fast and reliable method for performance evaluation, compatible with the timing of design evolution. The CFD methods for manoeuvrability assessment represent a necessary intermediate step between preliminary tools and model tests. Compared to previously used numerical tools, the newest methods allows reliable quantitative calculation of submarine performances.

These new CFD methods were developed by Naval Group for the past decade, on the basis of a RANS solver. The simulation options and meshing strategy were defined to take into account the specificity of the flow around a submarine. For efforts calculation, steady state input flow on a fixed model is simulated. For the direct calculation of manoeuvring performance such as the turning diameter, the equations of the submarine dynamics are solved at the same time as the equations of fluid.

The CFD based approach was validated by comparison with sea-trials and model tests on several submarines. This comparison confirmed the relevance of these methods for submarine manoeuvring performances analysis.

This calculation method is also well adapted and used to improve the evaluation of manoeuvring performance in shallow water.

5 References

[1] A. Bovis, Hydrodynamique navale, le sous-marin, Les presses de L'ENSTA (2010)

[2] PM. Guillouet, J. Raymond, Bassin numérique et modèle libre générique (ATMA 2014)

[3] S.L. Toxopeus, Practical application of viscous-flow calculations for the simulation of manoeuvring ships, PhD Thesis (2011)

[4] S. L. Toxopeus and al, Collaborative CFD Exercise for a Submarine in a Steady Turn, 31st International Conference on Ocean, Offshore and Arctic Engineering (2012)

[5] P. Carrica, CFD Simulations and Experiments of a Maneuvering Generic Submarine and Prognosis for Simulation of Near Surface Operation, 31st Symposium on Naval Hydrodynamics (2016)

[6] M. Bettle, Unsteady Computational Fluid Dynamics Simulations of Six Degrees-of-Freedom Submarine Manoeuvres, PhD Thesis (2012)

[7] B. Overpelt and al, Free Running Manoeuvring Model Tests On A Modern Generic SSK Class Submarine (BB2), Pacific International Maritime Conference (2015)

[8] B. Anderson and al, Experimental and Computational Investigation of a Generic Conventional Submarine Hull Form, 29th Symposium on Naval Hydrodynamics (2012)

[9] G. Vaz and al, Calculation of Manoeuvring Forces on Submarines using two Viscous-Flow Solvers, 29th International Conference on Ocean, Offshore and Arctic Engineering (2010)

[10] C.-Y. Tsai and A. Whitney, Numerical study of three-dimensional flow separation for a 6:1 ellipsoid, 37th Aerospace Sciences Meeting and Exhibit (1999)

[11] M. Bettle, S.L. Toxopeus, A. Gerber, Calculation of bottom clearance effects on Walrus submarine hydrodynamics. International Shipbuilding Progress, pp. 101–125, (2010)

[12] B.S. Wu, F. Xing, X.F. Kuang, Q. Miao Investigation of hydrodynamic characteristics of submarine moving close to the sea bottom. Journal of ship Mechanics , 9 (3), 19-28 (2005)

[13] A.I. Korotkin, Added masses of ship structures (2008)