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Numerical Approaches for Submarine Hydrodynamic Design and Performance Analysis

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Abstract. Submarines bring many interesting hydrodynamic challenges that need to be properly addressed to provide precise and reliable information about their performance. Hydrodynamic performance must be evaluated at least in two main operating conditions, namely when it is deeply submerged and at snorkel depth. There are relevant differences in terms of hydrodynamic since the forward speed in the latter condition is typically much lower and of interaction with the free surface. Moreover, submarines used to sail at snorkel depth if they need to accomplish specific tasks, such as communication, that involves the use of surface piercing masts. The proposed study analyses the opportunity provided by different Computational Fluid Dynamic (CFD) approaches to correctly address submarine performance. The resistance in both conditions, masts free surface hydrodynamics and maneuvering behaviors are addressed. *Ad-hoc* approaches based on in-house developed numerical procedures and open-source software are presented. Different CFD techniques have been used, including Reynolds Averaged Navire Stokes (RANS), Detached Eddy Simulation (DES) and Smoothed Particle Hydrodynamics (SPH), according to the particular physics that need to be studied.

Keywords. Submarine, Computational Fluid Dynamics (CFD), Resistance, Maneuvering, Free surface flow

1. Introduction: CFD Methods for Submarine Hydrodynamics

Submarines are assets of outstanding importance to implement strategies aimed at control and protection of maritime domain. The fulfillment of their tasks and the successful completion of their operational profiles imply attentive investigations during the design phase. Speed and range, for example, are among the most significant performance that need to be assessed, in relation to the submarine size and energy supply systems. The identification of the appropriate submarine configuration, able to comply with operational requirements, from one side is the result of systemic view that can guarantee that the high level performance are accomplished. On the other side, specific studies and analysis are necessary focusing for example on innovative energy system and storage solutions, innovative materials, structural details, hydrodynamic assessments. The per-

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formance of the submarine from the hydrodynamic point of view is given by the selected overall aspect ratio, the geometry and the position of sail, rudders and other appendages and it may be wide and complex. In fact, beside the compliance with design requirements relevant to speeds (surface, underwater, full speed, cruise speed, special operations speed,...) the hydrodynamic analysis of a submarine needs also to address also the maneuvering characteristics, under different circumstances. The performance prediction capabilities during the design phase is largely enhanced by the availability of appropriate simulation tools, that usually need to be specifically customized for the submarine, with its several peculiarities with respect to surface ships. Also the hydrodynamic investigations, though based of fundamentals share with surface ships, need a specific competence and knowledge due to submarines peculiar features. The best methodological approach together with the more appropriate calculation tool are to be identified in relation to the assessment aim.

Three CFD methods have been applied to study different problems related to submarine hydrodynamics. Global resistance performance have been analyzed by a Reynolds Averaged Navier Stokes (RANS) method. Detailed vortex structures in particular conditions have been predicted by exploiting the features of a Detached Eddy Simulation (DES) approach. Strongly non-linear free surface interactions with submarine masts and antennas have been studied by using a Smoothed Particle Hydrodynamics (SPH) technique. The first solver, provided by the open-source *OpenFOAM* suite, is a finite-volume based code designed to handle unstructured polyhedral meshes. This code solves the flow field, Navier-Stokes, equations in the turbulent regime. The most widely used turbulence treatment is based on the Reynolds decomposition (RANS), which averages the equations neglecting the direct evaluation of the turbulent fluctuations, but including their effects in the solution. The $SST k-\omega$ model (1) has been used since it is suitable for evaluating the mean forces of a moving body (2; 3; 4). When the free surface has an important role in the developed hydrodynamic forces, a multi-phase approach needs to be introduced. This adds a new set of equations that describe the evolution of the phase concentrations into the domain, accordingly to the Volume of Fluid (*VoF*) approach. The RANS approach suffers significant numerical damping. This effect makes the body's wake field smoother than the real one. Therefore, when the flow structures detached by the hull is of particular interest, a more conservative turbulence solution should be used. Then, to analyse the possible interactions of the hull vortex structures with the propellers, a Detached Eddy Simulation (DES) approach has been used. RANS equations in the free-stream region, far from the wall boundaries, are modified to directly solve the turbulent fluctuations whose sizes exceed the space discretization and modelling the remaining parts by using a sub-grid turbulence model. This approach requires a much higher computations effort that makes it not suitable for ordinary industrial studies but to analyse specific problems. A mesh-less method based on Smooth Particle Hydrodynamic (SPH) has been used for free surface masts hydrodynamics. The flow kinematics is described by means of the motion of particles interacting with each other and with the domain boundaries in a Lagrangian framework. This approach is particularly suitable when abrupt free-surface distortions are present, as in wave-breaking or spray phenomena, that is the case of the submarine sailing at snorkel conditions.

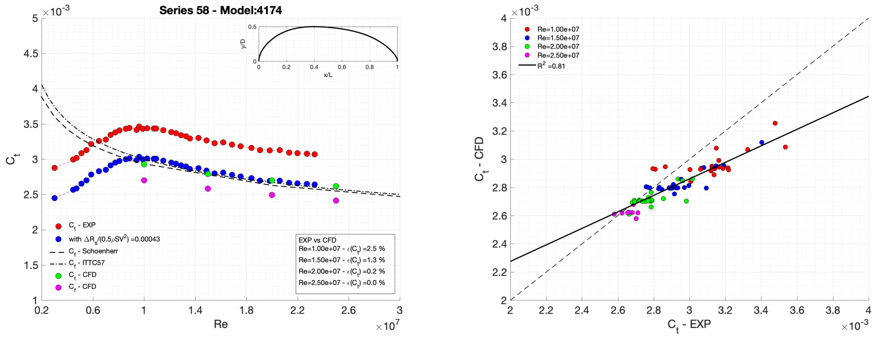

Figure 1. Left: Example of prediction for the model 4174 of the Series 58. Right: Correlation between the predicted and the experimental results for all the Series 58 models.

2. Hydrodynamic Prediction of Submarine Resistance and Flows

The resistance of different hulls, ranging from simple bodies of revolution up to a fully appended submarine design, is studied by using the previously mentioned RANS approach, to assess the numerical uncertainty of the method then providing a basis for further applications focused on specific, more realistic, vessels.

2.1. Revolution Bodies: the Series 58

The revolution bodies of the *Series 58* (5) have been analyzed. Four Reynolds numbers have been studied, in the range $Re = [1.0e^{+07}, 2.5e^{+07}]$. Numerical results have been compared against experimental measurements for the 24 models of the series. Figure 1 displays an example of results. The experimental measures (red circles) are corrected to include the friction induced by the strut used in the experimental set-up (blue circles). Numerical C_t (green) and C_f (pink) are shown to highlight the viscous, pressure-related contribution. ITTC'57 (6) and ATTC'47 (7) friction lines are shown too. The numerical predictions are in very good agreement with both the experiments and the conventionally used friction formulations. The decay of the experimental resistance coefficient in the low Reynolds numbers range highlights the laminar to turbulent boundary layer transition. The correlation between the numerical predictions and the corresponding experimental measurements for all the series' models is shown in Figure 1. A high correlation coefficient, equal to $R = 0.81$, has been found considering all models of the series, proving that the numerical predictions are consistent with the measurements. The numerical predictions slightly underestimate the forces when higher coefficients are evaluated, that is when the laminar flow is more significant.

2.2. The DARPA SUB-OFF Model

The resistance performance of the *DARPA SUBOFF* hull at either deeply submerged (8) condition and close to the free surface (9) have been studied and compared to available experimental measurements. It is characterized by a cylindrical hull, a relatively tall and narrow (and quite unrealistic) fairwater, four equal rudders in a '+' configuration, and a propeller ring. Two configurations have been studied, called AFF-1 and AFF-8, corre-

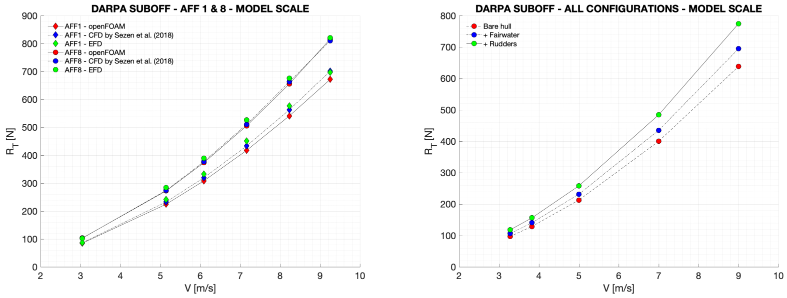

Figure 2. Comparison of the total resistance for the DARPA SUBOFF, configuration AFF-1 and AFF-8, respectively, at model scale. Left: the CFD vs. EFD; Right: the drag contribution of each appendage in fully appended condition.

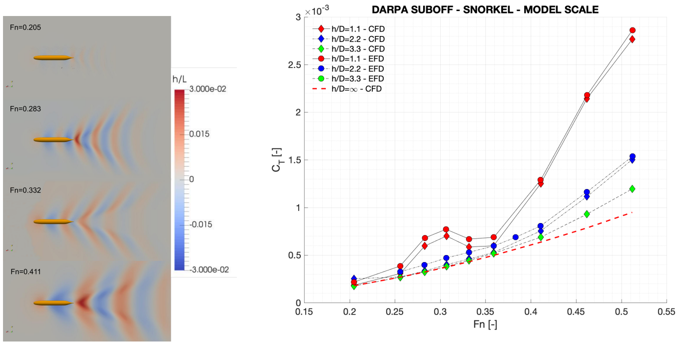

Figure 3. Comparison of the total resistance coefficient for the DARPA SUBOFF at snorkel depth (left) and the wave elevations for $h/D = 1.1$ (right).

sponding to the bare hull and the fully appended one, respectively. The numerical predictions for both configurations are compared to experimental measurements and to other CFD results (10) in Figure 2, highlighting a slightly better agreement with the experiments for the fully-appended configuration. This can be partially ascribed to the experimental uncertainty. Figure 2 displays the resistance curve for incremental configurations of the DARPA-SUBOFF, i.e. the bare hull, bare hull with the fairwater and the latter including the rudders. Each appendage introduction increases the overall resistance. On average, the fairwater introduces an increase of the resistance of about 8.8%, while the rudders generate a higher increase of the total resistance, in the extent of 12.5%. The predicted total resistance coefficient at snorkel depth is compared to available experimental measurements in Figure 3, at three distances from the free-surface, corresponding to $h/D = [1.1; 2.2; 3.3]$. At the depth ratios $h/D = [2.2; 3.3]$ the free surface proximity introduces effects for $Fn > 0.4$, due to a more relevant wave formation. For the same reason, the lower depth ratio $h/D = 1.1$, the C_t curve presents an abrupt hump at $Fn = 0.3$. Such a hump is then damped thanks to a positive interference of the waves, resulting in a cancellation of most of the contributions. This is also displayed in the non-dimensional wave patterns in figure 3. At $Fn = 0.332$, the stern wave indeed cancels out the leading waves, reducing the wave heights.

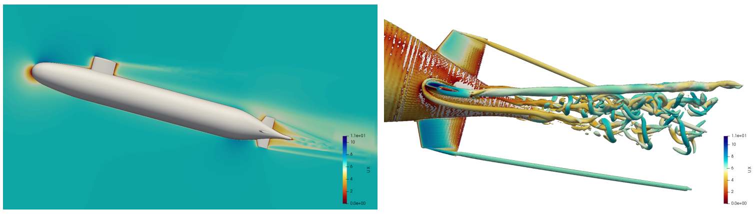

Figure 4. Vortexes structures detached by the stern region during a severe manoeuvring condition.

3. Flow Structures in particular Conditions: DES Computations

Beyond classic resistance performance predictions in steady conditions, which are of major interest for the design conditions, additional analysis can be carried out in peculiar off-design conditions, such as when the vessel assumes a significant angle of attack, e.g. for emergency diving or surfacing. In these types of manoeuvring, stronger vortex structures are detached from the hull. Such a vortexes, depending on their strength, can move astern then interacting e.g. with the propellers. In these conditions, more complex simulations can be performed based on the DES method, as shown in figure 4. This type of results might be useful to predict specific features of the submarine.

4. Maneuvering

A manoeuvring model for the dynamics of underwater vehicles has been established for design-aid and operation simulation purposes in six degrees of freedom. The approach develops a fully modular and parametric MMG-approach (11; 12) based on the revised Gertler-Feldman equations (13; 14), which gathers Admiralty Experiment Works-Haslar knowledge (15) and in-house experience in manoeuvring hydrodynamics (16; 17; 18; 19; 20). The bare hull is studied by using a sectional slender body framework enables the evaluation of the linear lift component, thanks to a strip-theory modelling with 3D viscous corrections, and the non-linear terms, according to the implementation of the cross-flow drag theory for vortex shedding terms at higher angles of attack. The hydrodynamic lift and drag of the bridge fin is based on low aspect ratio and crossflow drag wing theory, by including both the increased effectiveness and amplification factor provided by the hull-mounting based on the local radius of the elliptical body. Control planes and the rudders are evaluated both at pre- and post-stall based on main geometrical characteristics of horn, skeg, spade and flap designs. The thrust and torque hydrodynamic modelling of the propeller includes open-water 4-quadrant series, by varying blade number, expanded area ratio and pitch, plus an oblique flow representation of the unbalanced tangential and lateral force during drift and yaw motions. The trailing vortex down-wash generated by the tip of the bridge fin is modeled in terms of modification of the angle of attack of the downstream upper stern plane, depending on the drift and yaw attitude.

The method then allows to simulate the manoeuvrability performance in 6 DoF of a fully appended submarine. In particular, some specific trials can be carried out such as the Turning circles $(10^\circ, 20^\circ, 35^\circ)$, horizontal zig-zag $(10^\circ/10^\circ, 10^\circ/5^\circ)$, vertical zig-zag $(10^\circ/5^\circ, 5^\circ/5^\circ)$, Meander test and Jammed plane failures, such as deteriorated manoeu-

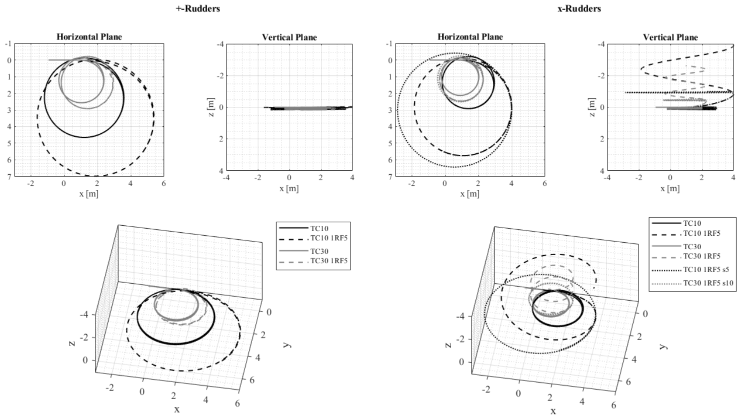

Figure 5. Manoeuvring – TC "+" vs "x"-config: intact and 1RF5 deteriorated condition

vring performances and dive fail crash stop. Figure 5 displays an example of the manoeuvring of a realistic unit. Considering an approach speed of 10 kn, where are compared the TC10 and TC35 features of the "+" and equivalent "x" configurations in the intact (solid line) and deteriorated (dashed line) conditions with the #1-stern plane jammed at -5 deg in the counter manoeuvring way, namely 1RF5. The configuration with 4-x redundant stern planes presents a significant advantage in the yaw direction, without particular loss of turning lengths, but still some dangerous trim attitudes could be overreach (in the example around 15°trim and 12°of heel, with consequent fast emersion speed). To compensate the dangerous trim condition, a differential control around the turning setting on the remaining planes should be realised to keep the track planar, i.e. 5°for the TC10 1RF5 s5, and 10°for the TC30 1RF5 s10.

5. Masts Hydrodynamics

The hydrodynamic design of the masts and antennas for a submarine involves highly fragmented free surface, wave breaking and spray phenomena. A SPH approach has been applied to account for highly non-linear wave transformations and wave-structure interactions (21; 22). The comparison of the highly turbulent wake developed behind two masts configurations, namely a single elliptic mast and three staggered masts, at the same forward speed, is shown in Figure 6. For the single mast there is an evident breaking,

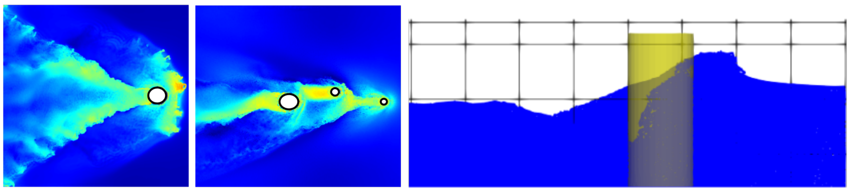

Figure 6. Example of wake formation behind two mast configurations and near field flow for overflow and pile-up studies. Left: single elliptic mast. Center: three staggered masts. Particle velocities are shown by the colormap. Right: flow elevation at the mast.

fragmented, wave crest in front of the mast itself and a turbulent wake dominated by two divergent wave fronts. When the same mast is included in the staggered configuration, preceded by two thinner masts there is an inception of a Karman vortex street behind the uttermost mast and resulting in a globally narrower wake field. The maximum height of the bow wave at the mast, related to the occurrence of the overflow from the top of the mast, is shown in the bottom of Figure 6.

6. Conclusions

Several Computational Fluid Dynamics methods have been applied to study the more significant design problems for submarines. Resistance predictions at both deeply submerged and snorkel depth, manoeuvring characteristics for specific trials, detailed vortex structures generation during steady drifting and the free surface hydrodynamics of submarine masts in different configurations have been analyzed. To this aim, different CFD methods have been applied, including RANS, DES and SPH. Each method has been selected based on its peculiar characteristics. RANS has been used for global performance analyses, DES has been applied to predict detailed vortex structures while SPH has been dedicated to predict non-linear free surface interactions. Moreover, a in-house manoeuvring model has been created and successfully applied to reveal submarine performance in different design configurations.

The presented results show that all the relevant hydrodynamic related issues involved in submarine design can be properly addressed by a suitable choice of the CFD approach.

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