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EFFECT OF DEPTH ON THE RESISTANCE OF THE DARPA SUBOFF BAREHULL USING CFD SIMULATION

Muhammad Sajjad Ahmad, Muhammed Amirul Asyraf Hasnan*,
Nik Mohd Ridzuan Shaharuddin,
Marine Technology Centre, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.
* Corresponding author: muhammedamirulasyraf@utm.my

ABSTRACT

This study presents a CFD analysis of the DARPA Suboff barehull configuration near the free surface, focusing on the effect of depth on hydrodynamic resistance. Simulations were carried out using ANSYS Fluent to examine the drag forces acting on the submarine hull at various depths. The results were validated by comparison with published data, demonstrating good agreement. Special emphasis is placed on the impact of the hull's proximity to the free surface, which significantly influences the resistance force and overall performance of the underwater vehicle during shallow-depth operations.

KEYWORD

DARPA Suboff, CFD, hydrodynamics, free surface, ANSYS Fluent

INTRODUCTION

Underwater vehicles operating near the water's surface experience unique hydrodynamic challenges due to the interaction between the hull and the free surface. Description of free surface is shown in Figure 1. This interaction significantly affects the vehicle's resistance, stability, and maneuverability (Zhang et al., 2024). As submarines move closer to the surface, wave formation, buoyancy variations, and changes in water pressure introduce complex forces that impact the vessel's overall performance. Predicting these forces accurately is critical for submarine design and operation, particularly during key maneuvers such as diving, surfacing, or maintaining shallow-depth operations. Computational Fluid Dynamics (CFD) has become an essential tool in predicting and analyzing these forces, as it allows detailed simulations of hydrodynamic interactions that are difficult to capture experimentally.

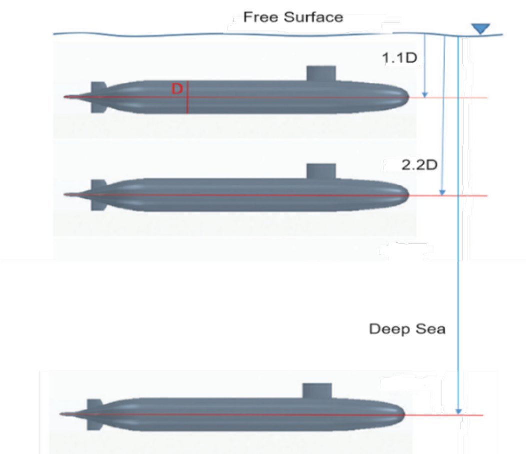

Figure 1: Description of Free Surface

Recent studies have highlighted the significant impact on hydrodynamic performance of underwater vehicles near the free surface using computational fluid dynamics (CFD) simulations. DARPA Suboff, which is a standard model for underwater vehicles has been widely used in hydrodynamic studies of the underwater vehicles (Groves et al., 1989). Many of these studies, however, primarily addressed submerged configurations, with fewer investigations dedicated to the effects of operating near the free surface. Additionally, while some experimental towing tank tests have been conducted, obtaining accurate results at varying depths close to the free surface remains a challenge due to wave interference and surface effects (Chen et al., 2024; Lambert et al., 2023). Comparisons between free surface and deep water effects reveal that the free surface has a greater influence on hydrodynamic forces (Ling et al., 2022). The research gap lies in a detailed CFD-based analysis of how proximity to the free surface influences the hydrodynamic performance of a submarine's barehull configuration.

This study aims to fill this gap by performing CFD simulations of the DARPA Suboff barehull near the free surface and deep water. The focus is on analyzing the impact of depth on hydrodynamic forces such as drag at various depths to understand the free surface effects. The objective of this study is to provide CFD-based results on the interaction between the hull and the free surface and to contribute to improved design and performance prediction of underwater vehicles operating near the surface.

METHODOLOGY

In this study, CFD approach was employed to investigate the effect of depth on the hydrodynamic forces acting on the DARPA Suboff barehull near the free surface. The simulations were conducted using ANSYS Fluent at a single speed of 3.045 m/s for three different depths (1.1D, 2.2D, and deep water). The following steps outline the methodology used for domain modeling, meshing, and solution setup.

Domain Modeling

The computational domain was created with dimensions sufficiently large to capture the free surface effects and avoid boundary interferences and shown in Figure 2. Model length is 3.356m and maximum diameter is 0.508m. The length of the domain was set to according to ITTC guidelines (ITTC, 2014), allowing adequate space for flow development around the submarine model. The DARPA Suboff barehull geometry was used for the simulations. Free surface was modeled at 1.1D and 2.2D and no free surface is modeled for deep water. The air-water interface was modeled using the Volume of Fluid (VOF) method, which allows for tracking the free surface. Velocity inlet and pressure outlet boundary conditions were imposed to simulate the free-stream flow conditions.

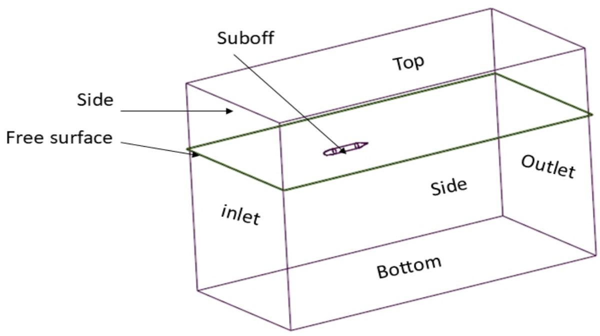

Figure 2: Domain Modeling

Meshing

Mesh was generated around the Suboff hull, with additional refinement near the hull surface and in the free surface region. Inflation layers were applied to the hull surface to resolve the boundary layer accurately, with a first layer height of 0.5 mm and 10 inflation layers. The smallest element size in the mesh was 10 mm, ensuring that the flow features near the hull and free surface were captured adequately. The mesh quality was checked to ensure a good aspect ratio and skewness, particularly in regions near the free surface and the hull, where sharp gradients in velocity and pressure are expected.

Solution Setup

The simulations were set up using the Reynolds-Averaged Navier-Stokes (RANS) equations with the k-ω Shear Stress Transport (SST) turbulence model. This turbulence model was selected due to its effectiveness in capturing flow separation and boundary layer phenomena, which are crucial near the free surface. The Volume of Fluid (VOF) method was employed to model the interaction between the air and water phases at the free surface. A velocity of 3.045 m/s was specified at the inlet, and the fluid properties were set to represent the water and air phases, respectively. The pressure outlet was set at zero-gauge pressure, and the hull was assumed to be stationary. A transient simulation was performed to capture the free surface dynamics and the behavior of the hydrodynamic forces. The convergence criteria for the simulations were set to residual values below 1e-6 for continuity and drag force was monitored to ensure they reached steady values. The Courant number was controlled to ensure stability in the solution, and a time step size of 0.01 seconds was used to capture transient effects, particularly in the free surface region.

Grid independence Study

Grid convergence study was conducted to ensure that the CFD results are independent of the mesh density. Three different mesh sizes were evaluated: coarse, medium, and fine. The resistance force was monitored at a depth of 1.1D for a speed of 3.045 m/s, and the results are plotted in Figure 2. the results for resistance force changes significantly as the number of elements increases, indicating the solution's sensitivity to mesh size in the coarse and medium mesh cases. However, from medium to fine mesh, the change in resistance force becomes minimal. This indicates that the medium mesh size is sufficiently refined to provide accurate results, achieving grid independence. For the remaining simulations, the medium mesh was used to balance computational efficiency and accuracy.

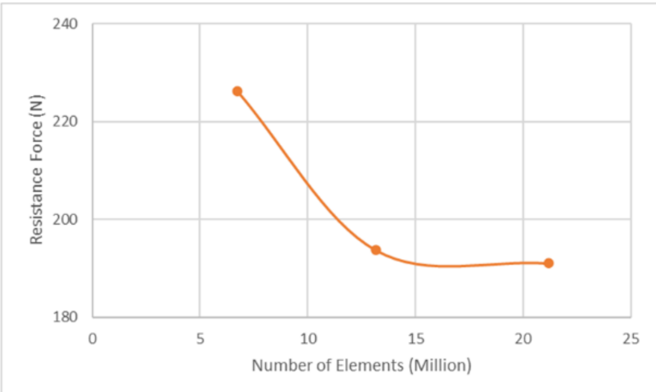

Figure 3: Resistance force with Three mesh conditions

RESULT AND DISCUSSION

The results from the present study's CFD simulations are shown in Figure 4. Results are compared with the Amiri et al., (2018) for the DARPA Suboff barehull at three different depths: 1.1D, 2.2D, and deep water. The depths correspond to the suboff's distance from the free surface, with increasing depths reducing the free surface effects. The slight differences can be attributed to variations in the numerical setup, including mesh resolution, turbulence modeling, or other CFD parameters. Nevertheless, the trends are consistent across all depths, confirming that the CFD approach employed in the present study yields reliable results for hydrodynamic resistance. As the depth increases, the resistance force acting on the barehull reduces significantly. At 1.1D, the proximity of the hull to the free surface leads to increased resistance, likely due to wave-induced effects and free surface interactions. At 2.2D, these effects reduced quickly, leading to a noticeable drop in resistance. In deep water, where the free surface influence is negligible, the resistance reaches its lowest value. This behavior aligns with the expected hydrodynamic trends, where vehicles operating closer to the free surface experience higher resistance due to wave formation and free surface effects. These findings emphasize the importance of considering operational depth in the design and performance analysis of underwater vehicles, particularly for near-surface operations where hydrodynamic forces can be significantly affected. Figure 5 represents the Hump and hole behavior at free surface and velocity contour of the domain.

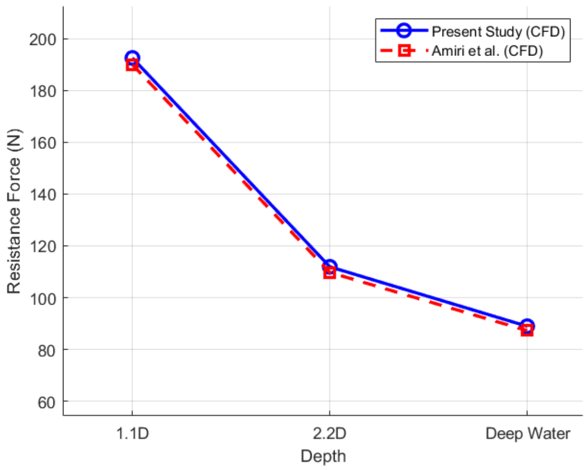

Figure 4: Resistance Force on DARPA Suboff at various depths

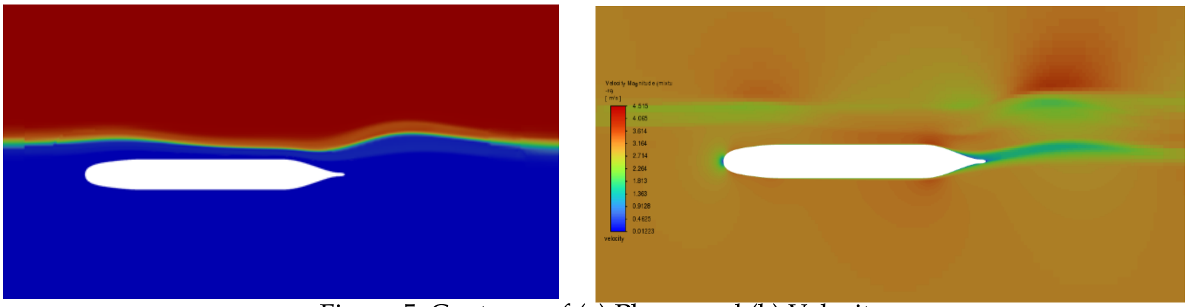

Figure 5: Contours of (a) Phase, and (b) Velocity

CONCLUSION

This study presents a detailed computational fluid dynamics (CFD) analysis of the DARPA Suboff barehull near the free surface at various depths, with the objective of investigating the effect of depth on hydrodynamic forces. The simulation was conducted using ANSYS Fluent, and a grid convergence study was performed to ensure solution accuracy. The results were validated by comparing them with previously published numerical data showing good agreement across all examined depths. The findings indicate that resistance force acting on the submarine reduces significantly as the depth increases. At 1.1D, near the free surface, the resistance is highest due to free surface interactions and wave-making effects. As the depth increases to 2.2D and deep water, the resistance decreases substantially, with the lowest resistance observed in deep water where free surface effects are minimal. The comparison of the present study's CFD results with those of Amiri et al. demonstrated that the CFD model accurately predicts the resistance forces for the DARPA Suboff barehull at varying depths, with only slight differences likely due to mesh refinement or turbulence modeling variations. This study underscores the importance of considering depth when analyzing the hydrodynamics of underwater vehicles, particularly when operating near the free surface. This is crucial for the design and optimization of submarine hulls, as vehicles operating at shallow depths experience higher resistance forces, which can affect performance and maneuverability.

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