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# Denizaltı Gövdesinden Türetilen Bir Formun Boyutsuz Hidrodinamik Katsayılarının Belirlenmesi

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## ÖZET

Bir deniz aracının gövde formu, bir veya birden fazla amaç için optimize edilebilir. Özellikle geminin akışkan kaynaklı direnç değerinin azaltılması amacıyla en uygun formu elde etmek temel amaçlardan biridir. Çünkü, enerji verimliliği söz konusu olduğunda, geminin formunu direnç açısından optimize etmek, daha az yakıt tüketimi anlamına gelmektedir. Bu amaçla daha önceki çalışmada yalın bir denizaltı formu ve bu denizaltının baş ve kıç formlarında çeşitli değişiklikler yapılarak elde edilen yeni denizaltı formları kıyaslanmıştı. Fakat, direnç açısından optimize edilen formun deniz aracındaki diğer dinamiklere etkisinin de araştırılması gerektiği düşünülmektedir. Bu sebeple, önceki çalışmada türetilen formlar arasında direnç açısından en uygun form ile denizaltı modeli farklı yazılım programları kullanıldığı için manevra açısından bir değerlendirme yapılması düşünülmüştür. Fakat önceki çalışmada hesaplamalar için kullanılan program bu çalışmadan kullanılan programdan farklı olduğu için ilgili denizaltı formlarının boyutsuz direnç katsayıları bu çalışmada tekrar elde edilmiştir. Çeşitli hızlar için elde edilen bu boyutsuz direnç katsayıları birbirleriyle ve deneysel verilerle karşılaştırılmıştır. Çalışmanın ana amacı manevra açısından denizaltı formlarını kıyaslamak olduğu için çeşitli baş açıları için kuvvet ve moment değerleri elde edilmiştir. Böylece elde edilen değerlerden faydalanılarak her iki denizaltı yalın formuna ait $Y_v^{'}$, $Y_{vvv}^{'}$, $N_v^{'}$ ve $N_{vvv}^{'}$ boyutsuz hidrodinamik katsayıları hesaplanmıştır. Böylece hem denizaltı yalın gövdesinin hem de bu denizaltından türetilmiş yeni formun manevra açısından değerlendirilebilmesi mümkün olacaktır.

**Anahtar kelimeler:** Darpa Suboff, Manevra, Hesaplamalı akışkanlar dinamiği (HAD), Statik sürüklenme

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Research Article

# Non-dimensional Hydrodynamic Coefficients Determination of a Derived-Submarine Bare Hull Form

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## ABSTRACT

The hull of the marine vehicle can be optimized based on the target one or more purposes. One of the most frequent purposes is the form optimization to obtain the most suitable form in terms of resistance. When it comes to energy efficiency, optimizing the vessel's form in terms of resistance means less fuel consumption. However, it is thought that the effect of the optimized form on other dynamics in the marine vehicle should also be investigated. Resistance coefficients were obtained for this purpose by constructing various bow and stern forms for a simple submarine form. The resistance coefficients of both the submarine and the form derived from this submarine were validated again in this study since different software programs were used in the previous study. These dimensionless resistance coefficients obtained for various velocities were compared to each other and the experimental data. Furthermore, the static drift analyses are performed to obtain the sway force and yaw moment at various attack angles. The dimensionless hydrodynamic coefficients, such as $Y_v$' and $N_v$', have been calculated with fitting a curve to the values of sway forces and yaw moments. The non-dimensional hydrodynamic coefficients differences calculated for the submarine and derived bare hull are close to each other when compared in terms of maneuvering derivatives.

**Keywords:** DARPA Suboff, Sway force, Yaw moment, Maneuvering derivatives, Static drift.

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## 1. Introduction

Obtaining a suitable hull form in terms of less resistance is one of the most important parameters while designing marine vehicles. For this reason, the created suitable form in terms of resistance during the design directly affects the needed amounts of fuel to reach the desired speed. Since the lower the resistance of the marine vessel, the higher speeds can be achieved depending on the thrust force. For this purpose, in some ships, such as planing hulls, it is tried to obtain forms that will create minimum resistance in order for the ship to reach the desired high speeds. One of the goals is to reduce the wetted area while optimizing the form to reduce resistance, especially in planing hulls. However, it is not possible to reduce the wetted area in commercial ships, such as tankers, container ships, and planing hulls due to the decrease in the usage area. For this reason, to reach the desired cruise speed thanks to the current thrust force, forms that increase the resistance for bare hull are avoided.

Since the wetted area of a submarine could not be changed in fully submerged condition, the resistance value only changes with the speed of submarine. However, the resistance value for the surface vessel depends on both the wetted area of the submerged part and the speed of surface vehicles. As a result, it is even more important to design the form so that it does not disrupt the flow, thereby reducing resistance.

It is the most dependable method for developing models and conducting resistance experiment for each form. However, in terms of time and cost, it is not preferable to create a model of all forms and conduct experiments on these forms. For this reason, Computational Fluid Dynamics (CFD) method may be selected to calculate the resistance and/or self-propulsion of the marine vessel due to the obtaining the faster results and less expensive. For example, the resistance and self-propulsion analyses of the DARPA Suboff with propeller were performed using CFD, considering the propeller-hull interaction (Sezen et al., 2018). Similarly, a numerical study of the resistance and self-propulsion performances of the DARPA Suboff hull was studied under various conditions using CFD (Lungu, 2022). Another study, the resistance and self-propulsion parameters of the container ship model were obtained using CFD and compared to available experimental data (Lungu, 2020). In addition to these studies, different methods based on CFD approach can be chosen to determine the resistance and self-propulsion characteristics of a marine vessel (Delen et al., 2021).

The first experimental data of DARPA Suboff submarine is provided in the literature by Roddy (1990). This study includes not only static drift tests but also Planar Motion Mechanism (PMM) tests for various DARPA Suboff forms, such as bare hull, bare hull with sail, fully appended etc. Later, researchers made various experiments based on original DARPA Suboff form. For example, Lin et al. (2018) used a half-scale of DARPA Suboff form including various types, such as bare hull, bare hull with sail etc., in the experiments to determine the maneuvering derivatives. Other researchers, Efremov, and Milanov (2019) carried out experiments for DARPA Suboff form with various sailing conditions to investigate its course stability and hydrodynamic derivatives. In addition to the experimental studies, the CFD method is usually preferred by researchers to investigate the maneuvering derivatives. The maneuvering derivatives of DARPA Suboff submarine were obtained using the CFD method and compared to available experiment results (Duman et al.2018). CFD method was also used to get information about the scale effect on resistance and propulsion (Sezen et al., 2021; Dogrul, 2022), the horizontal maneuvering derivatives (Kahramanoglu, 2023), and the performance of propulsion (Kinaci et al. 2018). Other studies, obtaining the effect of the forward speed of a ship on the side translation and yaw moment are measured using CFD method (Kahramanoglu, 2021), and the turning and course-keeping abilities are evaluated for a submarine using direct CFD method (Delen and Kinaci, 2023).

The purpose of this research is to compare the newly derived form to the DARPA Suboff bare hull in terms of maneuverability. In the previous study,  the dimensionless resistance coefficients of derived form at different speeds were obtained, and it was emphasized that it was a more suitable form than the DARPA Suboff form. However, the verification and validation studies are necessary in this study since the mesh structure and domain are created in a different program than in the previous study. The resistance coefficients were obtained for different speeds to validate the mesh structure and calculations because of this requirement. After the validation of the generated domain was shown, and thus sway force and yaw moment are calculated using static drift analyses performed same computational domain to determine the maneuvering derivatives. As a result, dimensionless hydrodynamic coefficients were determined for the obtained force and moment values using CFD method, and both forms were evaluated in terms of maneuvering.

## 2. Numerical Modelling

Since the simulations performed in the present study is time independent, the flow was assumed as steady in all numerical analyses. In addition to this, the flow around the submarine was presumed as 3D, fully turbulent, and incompressible. To model the fully turbulent model, k-epsilon turbulence model was selected. Similar to the relevant studies in the literature (Marshallsay and Erikksson, 2012; Kahramanoglu, 2023), the governing equations was conservation of momentum (RANS) and conservation of mass (continuity). The detailed information about the physical modelling and turbulence model can be investigated in the study (Wilcox, 2016).

### 2.1. Geometric Description

DARPA Suboff bare hull and different bow and stern form derived from its form, namely Form 13, were obtained, and evaluated in terms of the resistance for various velocities in previous study (Budak and Beji, 2016).  The basic dimensions of the DARPA Suboff bare hull and Form 13 are given in Table 1.

**Table 1.** The main dimensions of DARPA Suboff

| **Main Dimension** | | **DARPA Suboff** | **Form 13** |
|---|---|---|---|
| **Length Overall** | $L_{OA}$ **(m)** | 4.356 | 4.356 |
| **Diameter** | ***D*** **(m)** | 0.508 | 0.508 |
| **Wetted Area** | ***S*** **($m^2$)** | 5.98 | 6.036 |
| **Longitudinal Center of Gravity** | ***LCG*** **(m)** | 0.169 | 0.166 |

The geometries for DARPA Suboff bare hull and Form 13 are shown in Figure 1. The overall length ($L_{OA}$) and the maximum diameter ($D$) are the same for DARPA Suboff bare hull and Form 13. Although the wetted area of DARPA Suboff bare hull is 5.98 $m^2$, Form 13 has 6.036 $m^2$ wetted area. Moreover, the longitudinal center of gravity of Form 13 is 0.166 m.

### 2.2. Computational Domain and Boundary Conditions

A rectangular computational domain was created in viscous based solver to investigate the hydrodynamic characteristics of DARPA Suboff and Form 13. The domain extended 1.5 $L_{OA}$ in front of the submarine, 5.0 $L_{OA}$ behind the submarine, 5.0 $L_{OA}$ between left side and right side of the submarine. The depth of the computational domain was determined as 5.0 $L_{OA}$. The details can be seen in Figure 2. Since the flow passed through the computational domain in negative x direction, the right side of the computational domain was selected as velocity inlet while the left side of it was pressure outlet. All other boundaries, such as bottom, top etc., were selected as velocity inlet. The submarine forms were selected as no-slip wall to satisfy the kinematic boundary condition.

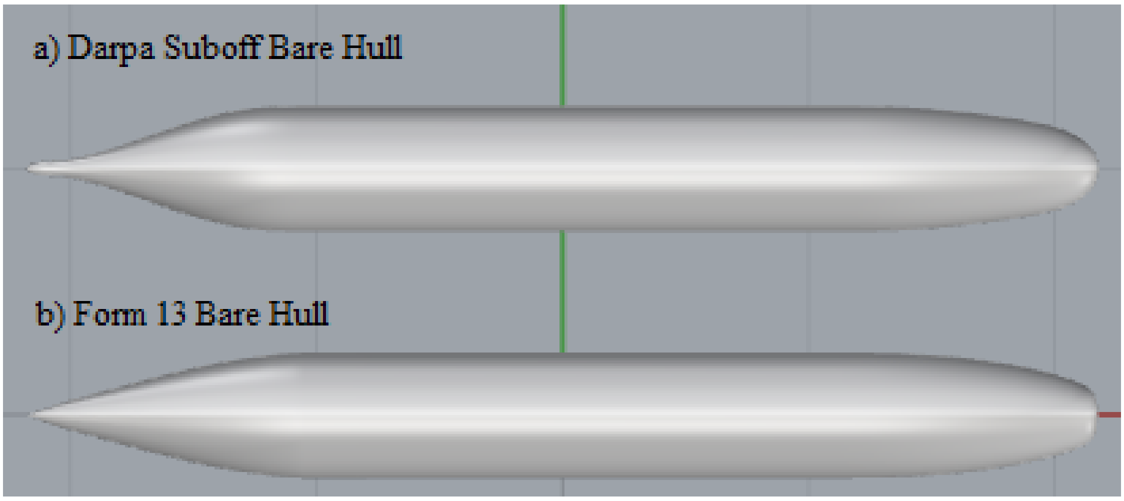

**Figure 1.** The geometries a) DARPA Suboff Bare Hull, b) Form 13 Bare Hull

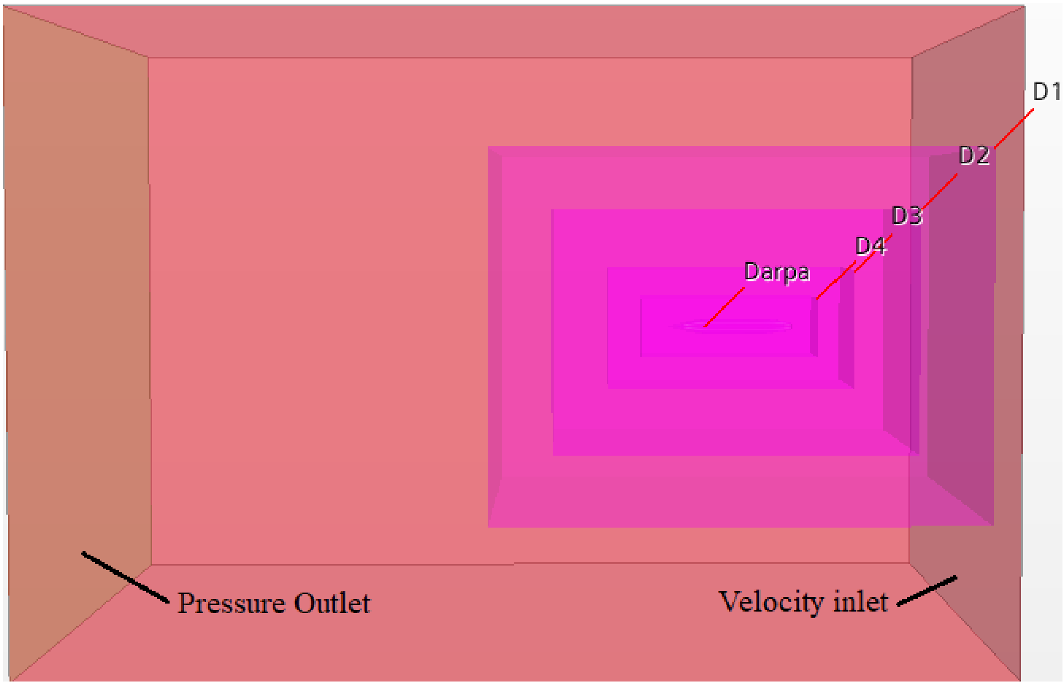

**Figure 2.** The determined computational domain

### 2.3. Grid Structure and Physical Modelling

The computational domain was divided into small cells by using hexahedral elements. The grid structure was refined towards the submarine forms while it was enlarged in far zone to reduce the computational time. The grid structure used in the present study can be seen in Figure 3.

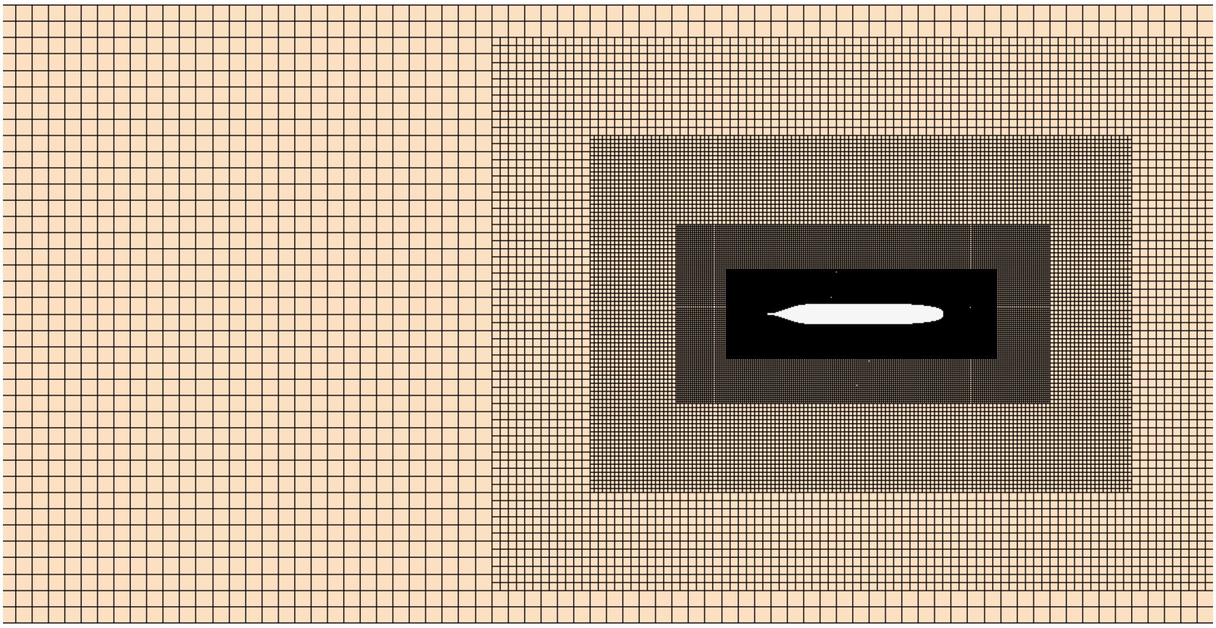

**Figure 3.** The transition of mesh structure around the geometry

The views of mesh structures shown both near and on geometry are given in Figure 4.

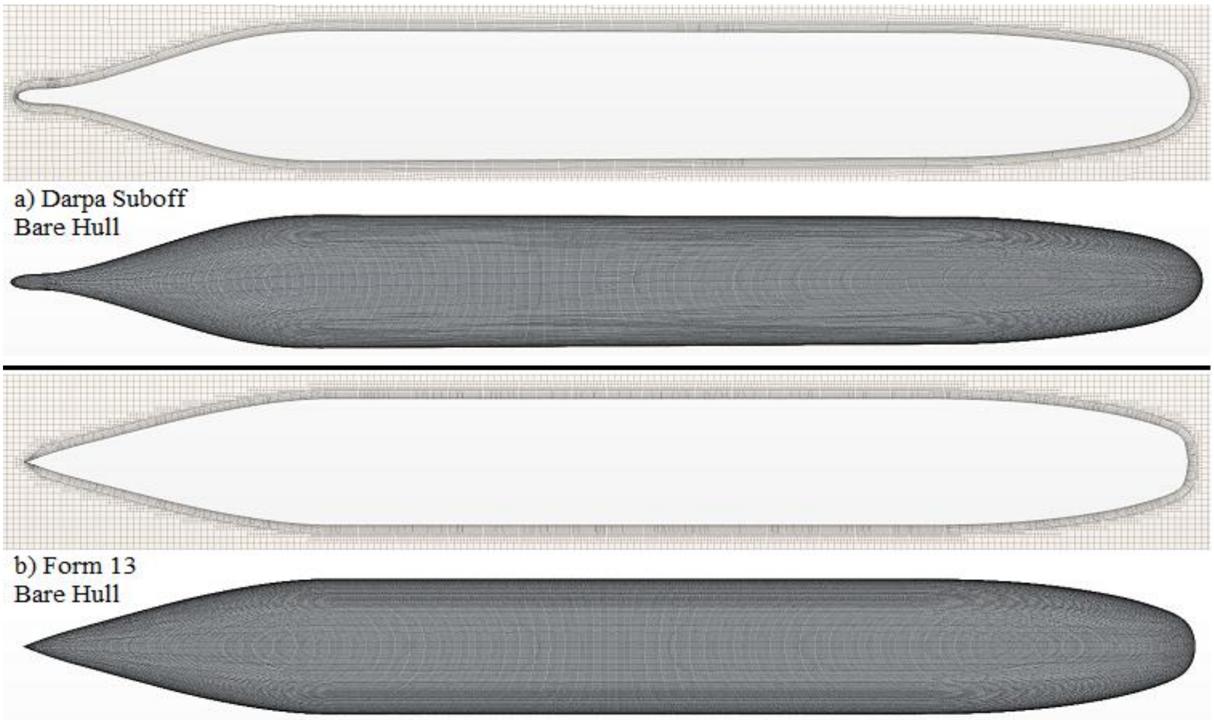

**Figure 4.** The view of mesh structures at y=0, a) DARPA Suboff Bare Hull, b) Form 13 Bare Hull

## 3. Results

In this study, Form 13, which is a more suitable form with a lower resistance coefficient, was evaluated in terms of maneuver. In order to reach this aim, the first part of the study is the towing tank analyses of DARPA Suboff bare hull, and the results were compared with the available experimental data. The second part of this study is the oblique towing tank simulations conducted both for DARPA Suboff and Form 13 and the results were compared with each other.

### 3.1. Verification and Validation

In the previous study, the resistance values for various velocities of submarine were validated for the DARPA Suboff bare hull. However, since a different software program was used in this study, it was thought that the verification and validation studies should be done again. The computational analyses for three different element numbers, namely coarse, medium, and fine, have been performed for a selected velocity to verify the mesh structure. The methodology presented by Celik et al. (2008) was followed to implement Grid Converge Index (GCI) method based on Richardson Extrapolation (1910) for the verification study. The element numbers of the mesh structure created for the defined computational domain are given in Table 2. The converged resistance value depending on the element numbers is given in Figure 5.

**Table 2.** The element numbers in computational domain.

| | Element Number |
|---|---|
| Coarse | $1.33 \times 10^5$ |
| Medium | $2.66 \times 10^5$ |
| Fine | $6.51 \times 10^5$ |

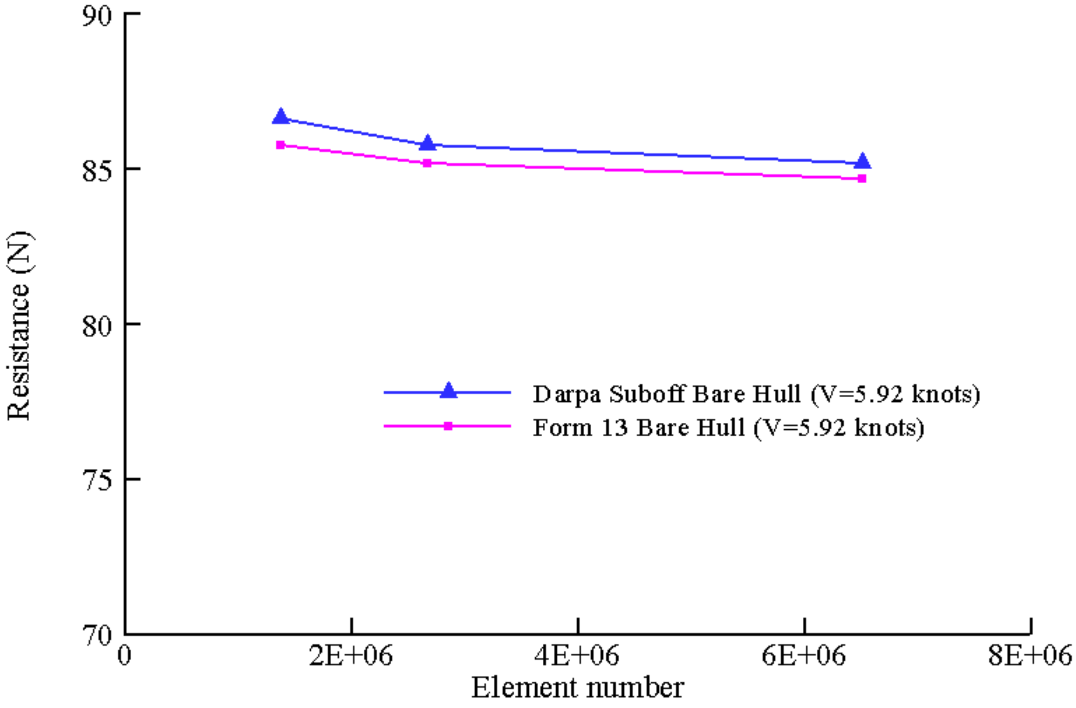

**Figure 5.** The results of the total resistance depending on element number

The uncertainty values in terms of resistance for DARPA Suboff bare hull and Form 13 bare hull are presented in Table 3. The differences between experimental data and CFD result for Fine mesh structure is 2.54 %. According to the Table 3, the grid spacing has monotonic convergence regime

(0<R<1) and the uncertainty values are within acceptable levels. The parameters, r: refinement factor; R: the convergence factor; p: apparent order; U%: uncertainty value.

**Table 3.** Uncertainty assessment

| | | **DARPA Suboff** | **Form 13** |
|---|---|---|---|
| **Total Resistance (N)** | **Fine** | 85.18 | 84.68 |
| | **Medium** | 85.76 | 85.17 |
| | **Course** | 86.61 | 85.78 |
| | **EFD** | 87.40 | - |
| **The parameters** | **r** | 1.414 | 1.414 |
| | **p** | 1.107 | 0.617 |
| | **R** | 0.682 | 0.807 |
| | **U %** | 1.831 | 3.059 |

### 3.2. Resistance Results

The first part of this study includes the calculation of the resistance values of a submarine for various speeds using Computational Fluid Dynamics (CFD) method. The experimental resistance value at each known speed and the obtained resistance value are given in Table 4. When the experimental and CFD results are compared, the errors for the low and high velocity values are lower than the errors obtained for the other velocity values.

Second part of this study, the dimensionless resistance coefficients obtained for the DARPA Suboff bare hull were calculated using $R_T = \frac{1}{2} C_T \rho S V^2$ equation. Where, $\rho$ is the density of water, $S$ is the wetted area of submarine hull, V is the velocity of submarine. Similarly, the dimensionless coefficients of Form 13 bare hull were calculated for various velocities using both same computational domain and same mesh structure used for DARPA Suboff bare hull resistance analyses. The dimensionless resistance coefficients obtained for each velocity value are given in Table 5. Additionally, these dimensionless resistance coefficients depending on velocity of submarine is shown in Figure 6. According to the Figure 6, the resistance coefficients obtained using the CFD method for the proposed form at each velocity are lower than the resistance coefficients of DARPA Suboff bare hull.

**Table 4.** The comparison of resistance values for DARPA Suboff bare hull

| **Velocity (knots)** | **Resistance (N)** | | **Error (%)** |
|---|---|---|---|
| | **Exp.** | **CFD** | |
| 5.92 | 87.4 | 85.18 | 2.54 |
| 10.00 | 242.2 | 227.04 | 6.26 |
| 11.84 | 332.9 | 311.41 | 6.46 |
| 13.92 | 451.5 | 421.55 | 6.63 |
| 16.00 | 576.9 | 547.06 | 5.17 |
| 17.99 | 697.0 | 681.27 | 2.26 |

### 3.3. Oblique Towing Tank Simulations

The values of sway forces and yaw moments obtained for various drift angle at V=6.5 knots using CFD method and available experimental results for DARPA Suboff bare hull are given in Table 6. The differences of sway forces values between EFD and CFD results of DARPA Suboff bare hull are higher than differences of the longitudinal forces and yaw moments.

**Table 5.** The dimensionless resistance coefficients for DARPA Suboff and Form 13.

| V (knots) | DARPA Suboff $C_T*10^3$ (EFD) | DARPA Suboff $C_T*10^3$ (CFD) | Form 13 $C_T*10^3$ (CFD) |
|---|---|---|---|
| 5.92 | 3.161 | 3.081 | 3.035 |
| 10.00 | 3.070 | 2.878 | 2.837 |
| 11.84 | 3.011 | 2.816 | 2.776 |
| 13.92 | 2.954 | 2.758 | 2.719 |
| 16.00 | 2.857 | 2.709 | 2.672 |
| 17.99 | 2.730 | 2.669 | 2.632 |

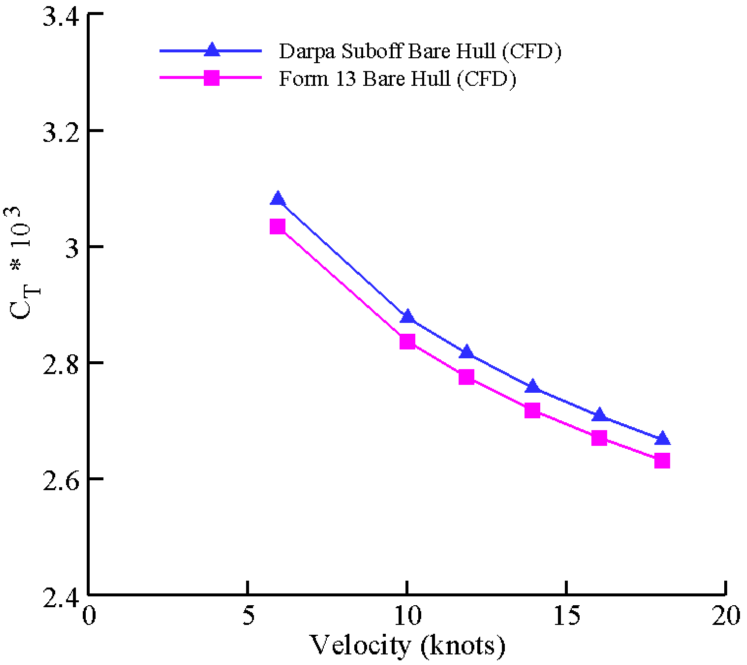

**Figure 6.** Non-dimensional resistance coefficient versus velocity.

**Table 6.** The comparison between experimental data and CFD results at V=6.5 knots.

| Drift | Darpa Suboff Bare Hull (EFD) | | | Darpa Suboff Bare Hull (CFD) | | |
|---|---|---|---|---|---|---|
| Angle | Long. | Sway | Yaw | Long. | Sway | Yaw |
| β (°) | Force (N) | Force (N) | Moment (Nm) | Force (N) | Force (N) | Moment (Nm) |
| 4.07 | -107.47 | 45.43 | 429.81 | -101.77 | 47.46 | 417.51 |
| 6.03 | -107.26 | 89.74 | 597.74 | -102.08 | 80.50 | 591.88 |
| 8.00 | -108.28 | 155.58 | 737.14 | -102.43 | 125.90 | 758.10 |
| 10.05 | -106.25 | 248.15 | 866.62 | -102.15 | 190.31 | 940.11 |
| 12.03 | -100.68 | 350.65 | 977.97 | -99.85 | 268.06 | 1080.77 |
| 13.94 | -92.56 | 464.50 | 1083.70 | -95.01 | 351.32 | 1213.00 |

The sway forces and yaw moments results for FORM 13 bare hull were obtained using same computational domain to compare the DARPA Suboff bare hull in terms of maneuvers. The results of CFD analyses are presented in Table 7.

**Table 7.** The forces and moments for Form 13 bare hull.

| | **Form 13 Bare Hull (CFD)** | | |
|---|---|---|---|
| **Drift Angle β (°)** | **Longitudinal Force (N)** | **Sway Force (N)** | **Yaw Moment (Nm)** |
| 4.07 | -101.18 | 49.63 | 417.10 |
| 6.03 | -101.46 | 83.51 | 604.89 |
| 8.00 | -101.73 | 129.42 | 779.11 |
| 10.05 | -101.28 | 193.36 | 942.21 |
| 12.03 | -98.77 | 270.16 | 1085.61 |
| 13.94 | -93.84 | 353.12 | 1219.87 |

When the results obtained with the CFD method for both bare hulls, Darpa Suboff and Form 13, are compared with each other, it is seen that there are small differences in both sway force and yaw moment values.

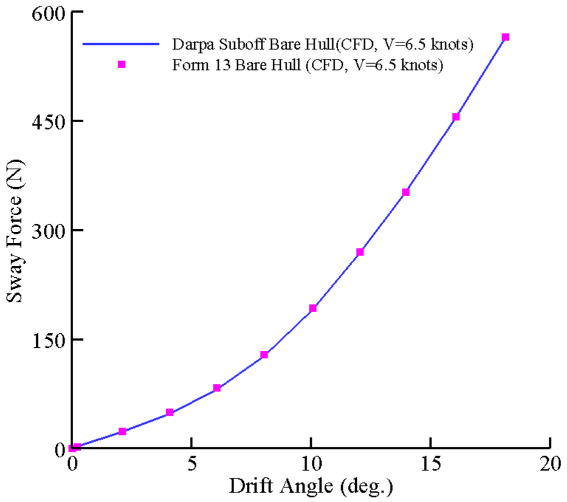

**Figure 7.** The comparison of the obtained sway forces.

The hydrodynamic derivatives of DARPA Suboff bare hull and Form 13 bare hull are calculated using Equation 1.

$$Y = Y_v v + Y_{vvv} v^3 \qquad (1)$$
$$N = N_v v + N_{vvv} v^3$$

where, v is the sway velocity.

The dimensional coefficients given in Equation 1 are converted to non-dimensional coefficients by the use of conversion factors given in Table 8.

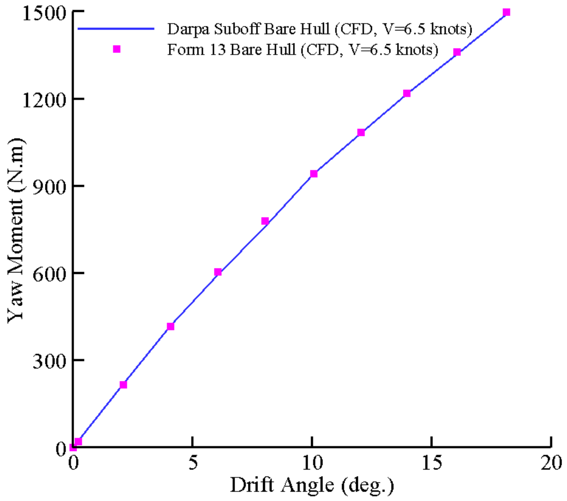

**Figure 8.** The comparison of the obtained yaw moments.

**Table 8.** Non-dimensioning factors.

| | **Non-dimensioning factor** |
|---|---|
| **Y** | $\frac{1}{2}\rho L^2 V^2$ |
| **N** | $\frac{1}{2}\rho L^3 V^2$ |
| **v** | V |

The non-dimensional hydrodynamic coefficients have been obtained by fitting a polynomial curve to the graphs of sway force and yaw moment, shown in Figure 7, and Figure 8, respectively. The details of how these dimensionless hydrodynamic coefficients are calculated can be found in the thesis of Yoon, H. (2009). The comparison of the non-dimensional hydrodynamic coefficients between experimental data found in the study of Roddy (1990) and the obtained results are given in Table 9.

**Table 9.** The non-dimensional hydrodynamic coefficents.

| | **Darpa Suboff EFD.** | **Darpa Suboff CFD** | **Form 13 CFD** |
|---|---|---|---|
| $Y'_v$ | -0.0059 | -0.0073 | -0.0075 |
| $Y'_{vvv}$ | - | -0.1138 | -0.1120 |
| $N'_v$ | -0.0127 | -0.0131 | -0.0132 |
| $N'_{vvv}$ | - | 0.0215 | 0.0226 |

## 4. Conclusion

The form, namely Form 13, including the most suitable bow and stern forms derived from DARPA Suboff bare hull in terms of resistance was proposed in the previous study. This form, which has the lowest resistance coefficient compared to the original submarine hull, is also considered to be evaluated in terms of maneuvering. Firstly, the created computational domain and mesh structure were verified to analyse the resistance of two forms, DARPA Suboff and Form 13. Secondly, resistance values were obtained for different velocities with the verified mesh structure and these results were compared with the available experimental results to validate the obtained results from analyses. Sway forces and yaw moments were measured for various drift angles to get information about the DARPA Suboff bare hull and Form 13 in terms of maneuvering. According to obtained results, sway force value for Form 13 at small angles (β≤10°) has an average of 3.48% higher compared to DARPA Suboff bare hull. However, this ratio at large angles (β>10°) is 0.53%. In addition, when the drift angle value increases, the sway force difference between the two models decreases. Similarly, the yaw moment difference at large drift angle is lower when compared to difference at small angles. Within the scope of this study, the results obtained at V=6.5 knots are considered the first step to obtaining the dimensionless hydrodynamic coefficients. Minor differences are observed between the maneuvering derivatives measured according to the sway force and yaw moment obtained for DARPA Suboff bare hull and Form13 bare hull. In this case, the more suitable Form 13 in terms of resistance may be preferred, but a more accurate interpretation can be made after other maneuvering derivatives are determined. For this reason, other dimensionless hydrodynamic coefficients may be obtained to evaluate the maneuvering performance of Form 13 in future studies.

## References

Budak,G. and Beji, S., 2016. Computational Resistance Analyses of a Generic Submarine Hull Form and Its Geometric Variants. *Journal of Ocean Technology* 11 (2), 2016.

Celik, I.B., Ghia, U., Roache, P.J., Freitas, C.J., Coleman, H., Raad P.E., 2008. Procedure for estimation and reporting of uncertainty due to discretization in CFD applications. J. Fluid Eng., 130 (7) (2008), pp. 78001-78004, 10.1115/1.2960953.

Delen, C., Can, U. and Bal, S., 2021. Prediction of Resistance and Self-Propulsion Characteristics of a Full-Scale Naval Ship by CFD-Based GEOSIM Method. *Journal of Ship Research*. 65. 346-361.

Delen, C. and Kinaci, O. K., 2023. Direct CFD simulations of standard maneuvering tests for DARPA Suboff. *Ocean Engineering*, Volume 276, 114202.

Dogrul, A., 2022. Numerical prediction of scale effects on the propulsion performance of Joubert BB2 submarine. *Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike,* 73(2), 17-42. https://doi.org/10.21278/brod73202.

Duman, S., Sezen, S. and Bal, S., 2018. Propeller Effects on Maneuvering of a Submerged Body. 3rd International Meeting - Progress in Propeller Cavitation and its Consequences: *Experimental and Computational Methods for Predictions* 15th – 16th November 2018, Istanbul, Turkey.

Efremov, D.V., Milanov, E.M., 2019. Hydrodynamics of DARPA SUBOFF submarine at shallowly immersion conditions. *The Int. J. Marine Navigat. Safety Sea Transport*, 13 (2), 337–342.

Kahramanoglu, E., 2021. The Effect of Forward Speed on Sway Force and Yaw Moment for Planing Hulls. *GMO Journal of Ship and Marine Technology*, Volume 220, December 2021.

Kahramanoglu, E., 2023. Numerical investigation of the scale effect on the horizontal maneuvering derivatives of an underwater vehicle. *Ocean Engineering*, Volume 272, 113883.

Kinaci, O. K., Gokce, M. K., Alkan, A. D., Kukner, A., 2018. On Self-Propulsion Assessment of Marine Vehicles. *Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike*, 69(4), 29–51. https://doi.org/10.21278/brod69403.

Lin, Y.H., Tseng, S.H., Chen, Y.H., 2018. The experimental study on maneuvering derivatives of a submerged body SUBOFF by implementing the Planar Motion Mechanism tests. *Ocean Eng*., 170, 120–135.

Lungu, A., 2020. Numerical Simulation of the Resistance and Self-Populsion Model Tests. *Journal of Offshore Mechanics and Arctic Engineering* 142(2):1-37, DOI: 10.1115/1.4045332.

Lungu, A., 2022. A DES-based study of the flow around the self-propelled DARPA Suboff working in deep immersion and beneath the free-surface. *Ocean Engineering*, Volume 244, 2022, 110358.

Marshallsay, P. G. and Eriksson, A. M., 2012. Use of Computational Fluid Dynamics as a Tool to Assess the Hydrodynamic Performance of a Submarine. *18th Australasian Fluid Mechanics Conference*, 3-7 December 2012, Launceston, Australia.

Richardson, L. F., 1910. The Approximate Arithmetical Solution by Finite Differences of Physical Problems Involving Differential Equations, with an Application to the Stresses in a Masonry Dam. Philos. *Trans. R. Soc. Lond*., vol. 210, 307-357.

Roddy, R. F., 1990. Investigation of the Stability and Control Characteristics of Several Configurations of the DARPA Suboff Model (DTRC Model 5470) from Captive- Model Experiments. Ship Hydromechanics Department Departmental Report, David Taylor Research Center, Departmental Report DTRC/SHD-1298-08, Sep. 1990.

Sezen, S, Delen, C., Dogrul, A. and Atlar, M., 2021. An investigation of scale effects on the self-propulsion characteristics of a submarine. *Applied Ocean Research*. 113. 10.1016/j.apor.2021.102728.

Sezen, S., Dogrul, A., Delen, C. and Bal, S., 2018. Investigation of self-propulsion of DARPA Suboff by RANS method. *Ocean Engineering*. 150. 258-271. 10.1016/j.oceaneng.2017.12.051.

Wilcox, D. C., 2016. Turbulence Modeling for CFD, third ed. DCW Industries, La Canada, California.

Yoon, H., 2009. Phase- Averaged Stereo-PIV Flow Field and Force/Moment/Motion Measurements for Surface Combatant in PMM maneuvers. Doctoral Thesis in Mechanical Engineering in the Graduate College of The University of Iowa, December 2009.