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Araştırma Makalesi

Doğadan İlham Alınarak Geliştirilen Bir Denizaltı Formunun Direnç Özelliklerinin Sayısal İncelemesi

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ÖZET

Doğa milyonlarca yıldır insanlara yuva olmanın yanı sıra, sunduğu sınırsız potansiyel ve kaynaklarla insanlar için geliştirilen çeşitli teknolojilerin en temel kaynağı olmaktadır. Bu çalışmada, doğadan ilham alınarak geliştirilen bir denizaltı formunun farklı hızlara karşılık direnç özellikleri Hesaplamalı Akışkanlar Dinamği (HAD) analizleri ile incelenmiştir. Bu kapsamda, öncelikle DARPA Suboff denizaltısının farklı hız değerlerinde HAD analizleri gerçekleştirilmiştir. Sayısal analizlerde, denizaltı etrafındaki türbülanslı akış Reynolds Ortalamalı Navier-Stokes (RANS) modeli SST Menter k-Ɛ türbülans modeli ile modellenmiştir. Uygulanan HAD yaklaşımlarının geçerlemesi, elde edilen sayısal sonuçlar ile literatürden alınan deneysel sonuçların karşılaştırılması ile sağlanmıştır ve hesaplama bölgesindeki ağ yoğunluğuna dayalı bir belirsizlik analizi ile doğrulaması gerçekleştirilmiştir. Daha sonra, köpekbalığı formunun geometrisiden ilham alınarak, DARPA Suboff denizaltısı ile aynı boyda ve aynı ortalama genişlikte bir denizaltı formu oluşturulmuştur. DARPA denizaltısı analizleri ile aynı HAD yaklaşımları kullanılarak ve aynı hidrodinamik koşullar oluşturularak doğadan esinlenerek oluşturulan denizaltının HAD analizleri gerçekleştirilmiştir. Aynı boy ve ortalama genişlikteki iki denizaltı formunun çeşitli hızlardaki toplam direnç değerleri kıyaslandığında, köpekbalığından esinlenerek geliştirilen formun direncinin daha yüksek olduğu tespit edilmiştir. Bu çalışmanın doğadan, özellikle de denizde yaşayan canlıların formlarından esinlenerek geliştirilecek yeni denizaltı çalışmaları için bir örnek olabileceği düşünülmektedir.

Anahtar kelimeler: HAD, RANS, DARPA Suboff Denizaltısı, doğadan ilham alan denizaltı tasarımı.

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Research Article

Numerical Analysis of Resistance Characteristics of a Submarine Form Inspired by Nature

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ABSTRACT

Nature offers unlimited potential in addition to being a home for people for millions of years, and people have developed a wide variety of technologies for themselves using the potential that the nature has bestowed. In this study, the resistance characteristics of a submarine form which inspired by nature, were investigated by Computational Fluid Dynamics (CFD) approach for various velocity conditions. Firstly, CFD analysis of benchmark DARPA Suboff Submarine are carried out for different velocity conditions. In the computational analysis, the turbulent flow around the submarine is modeled with Reynolds Averaged Navier-Stokes (RANS) model with k-Ɛ turbulence model to solve the governing equations. The validation of the CFD approaches applied was provided by comparing the numerical results with the experimental results obtained from the literature, and verified by performing an uncertainty analysis based on the grid density in the computational domain. Then, a submarine hull form with the same length and average width that of the DARPA Submarine is generated by using the geometry of the shark form as source of inspiration. Resistance values of the nature inspired submarine are predicted by using the DARPA Submarine CFD approach and the results are compared with the results of the DARPA Submarine for the same hydrodynamic conditions. For the same length and average width; the resistance of the shark inspired submarine is achieved slightly higher than that of the DARPA Submarine. This study is expected to be an example for the study of new submarines that will be developed inspired by nature, especially by the forms of various marine animals.

Keywords: CFD, RANS, DARPA Suboff Submarine, nature inspired submarine design.

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1. Introduction

Submarines are essential and specialized underwater vessels designed and built to perform underwater operations by the navy forces of many countries. They are used for a wide range of purposes such as underwater research, rescue and submarine warfare. Submarines have one of the widest ranges of types and capabilities of any vessel. Therefore, generating a new submarine hull form is a hot topic in marine engineering. Today, the modern submarines should be able to dive to the deepest part of the sea and have the ability to work at desired depth. From this point of view, design of a submarine is a very special and complicated engineering problem in terms of its strength, resistance and propulsion.

Nature-inspired design is using the nature as source of inspiration and create technical devices. Therefore, the nature-inspired design involves translating the information obtained from nature into new innovations. By observing and studying the form behavior, movement, adaptability and so on, people have developed new technologies or optimized existing ones inspiring from the animals or plants from the nature. For example, skin of a shark has the texture of sandpaper. It is covered in small ridged scales known as dermal denticles that optimize water flow. This excellent feature allows the shark to swim faster by reducing its frictional resistance (Feld et al. 2019). It is copied to reduce drag in boats. This has led to its further development and utilization in coatings for ship's hulls, submarines, aircrafts, and even swimwear for humans. Another example is that the geometry of the turbine blades are inspired by humpback whale fins. The humpback whales owe their agility to a row of ridges (tubercles) on the front edge of their fins. Called the tubercle effect, it markedly improves the aerodynamics of any airfoil by a significant amount. It leads to higher velocities by creating narrow streams of airflow and reduces the drag by reducing airflow over the wing-tips. The tubercle effect has used to reduce the drag and the noise and therefore to increase the speed of wind turbines. The biomimetic tubercle design has been applied to the corner shape on a deep-draft semi-submersible by Liang et al. (2019). A numerical study on flow over a deep-draft semi-submersible (DDS) with a biomimetic tubercle corner shape was carried out to investigate the corner shape effects on the overall hydrodynamics and motion responses.

In old times, researchers have studied the geometry of fish to make submarines. A steam powered submarine, the Ictíneo is a real example of fish inspired submarine presented in Figure 1 below. The submarine, made of olive wood supported with oak rings and sheathed in two-millimeter thick copper, measured 7 meters in length. The Ictíneo II was the first combustion engine driven submarine ever, pioneering concepts that were only rivalled in the 1940s (Url-1).

Despite its low-tech appearance, the Ictíneo was a sophisticated marvel of technology decades ahead of its time. It had a double hull, a spherical inner shell that resisted water pressure and a fish-like outer shell that protected the submarine and was used for steering and hydrodynamics (Url-2).

Figure 1. The Ictineo submarine inspired by fish (left) and Replica of the Ictíneo II submarine (right) (Url-1 and Url-2).

When the fish and submarine in the figures are examined, it is seen that the two are geometrically similar to each other.

The world's first combat submarine, also the first American military submarine named Turtle, was designed by David Bushnell and built in 1776 also was a nature inspired submarine. The name of the submarine had given as Turtle, because it was resembled "two upper tortoise shells of equal size joined together" (Manstan and Frese, 2010). Water was pumped in and out of the skin of the vessel to change its ballast, thus enabling the submarine to sink and rise. Thus, Turtle was the first submersible to use water as ballast for submerging and raising the submarine. Turtle was the first

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submersible to use a screw propeller, to maneuver under the water as well (Hunley, 2016). It had carried a single bomb and its mission was sabotage (Url-3).

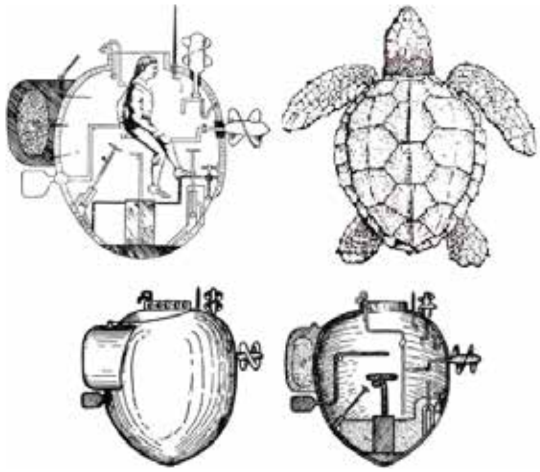

Figure 2. The world's first combat submarine (generated by the figures from Url-3 and Url4).

A more recent study is published by Ranjith et al. (2019) that investigates the manoeuvering properties of a fish-shaped unmanned under water vehicle (UUV). They generated a box-fish shaped under water vehicle form, which presented in Figure 3 and carried out 2-D CFD simulations to obtain forces and moments in heave and pitch motions of the vehicle. They suggested that 3-D models should be used for more accurate results.

Figure 3. A picture of boxfish (left) and three dimensional representation of the box-fish shaped UUV

generated from Ranjith et al. (2019) (right).

Researchers have been studied on hydrodynamics of submarines in recent years. Some of these studies are based on resistance prediction while the others investigate self-propulsion characteristics. In this study, the resistance characteristics of well-known he Defense Advanced Research Projects Agency (DARPA) SUBOFF bare hull (AFF-1) is investigated. Groves et al. (1989) described a mathematical formulation for the submarine form both for bare and appended cases. Huang and Liu (1994) and Liu and

Huang (1998) have performed experimental works for the DARPA Submarine model in David Taylor Research Center. Toxopeus (2008) performed viscous-flow calculations for bare hull of the submarine and Gross et al. (2011) predicted the resistance of DARPA submarine model with different angle of attack values using CFD and compared these results with the towing tank test results. Chase (2012) performed self-propulsion simulations on the submarine hull with the INSEAN propeller. Moonesun et al. (2013) used numerical methods to compute various available characteristics of Darpa submarine model and then compared their findings with relevant experimental measurements. Budak and Beji (2016) generated three slightly different bow and stern forms using the generic DARPA bare hull as the basis and conducted resistance analysis of these forms by CFD. Doğrul (2019) investigated the free surface effect for both bare and appended forms of DARPA Submarine in different velocity values.

In this study, CFD analysis of benchmark DARPA Submarine are carried out for different velocity conditions and validated with available experimental data in terms of total resistance values. Then, CFD analysis of newly generated submarine are performed with the same conditions that of DARPA Submarine and compared for the same velocity conditions. For the same length and width; the resistance of the shark inspired submarine was achieved slightly higher than that of a real submarine.

The submarine is one of the greatest human inventions inspired by nature in terms of its uses, design and role in military activities. Considering the history, it is seen that the development of the submarine was influenced by the geometric characteristics and swimming ability of the kinds of fish, whales and sharks in the sea. From this point of view, this study aims to contribute the nature inspired vehicles by presenting a newly generated a submarine hull form inspired by geometry of a shark.

This paper aims not only to contribute to a better understanding of nature inspired engineering, but also to offer new perspectives to improve the current drag reducing and energy saving technologies for submarine design.

2. Flow Simulations around DARPA Submarine Model

Flow simulations of the bare hull form of DARPA Submarine model are performed to compare the numerical results with the experimental ones and accordingly establish the grid generation details and set the computational parameters for ensuring satisfactory and reliable computational results.

Within the scope of the study, firstly the flow analysis around the DARPA Submarine are carried out. A commercial CFD software has been used for the mesh generation and flow simulations steps in the paper.

2.1 Geometry and Main Particulars

DARPA Suboff is a generic submarine model geometry with a length of 4.36 m comprising of 1.02 m fore body, 2.23 m mid body and 1.11 m aft body. It has a cylindrical cross-section with a maximum diameter

Figure 4. 3-D CAD model of the DARPA Suboff submarine.

of 0.508 m (Groves et al, 1989). Since the hull is axisymmetric, it is enough to obtain the complete surface the revolution of the curve around the symmetry axis. The hull of DARPA Suboff generated by a 3-D CAD software shown in Figure 4 below.

CFD analysis carried out modeling the flow around the DARPA Suboff Submarine. Main particulars of DARPA Suboff submarine used in this work are presented in Table 1 (Toxopeus, 2008).

Table 1. Main particulars of the bare hull DARPA Suboff submarine model.

Description	
Scale ratio, λ	24.0
Length overall, L_{OA}	4.356 m
Length between perpendiculars L_{PP}	4.261 m
Maximum hull radius, R_{max}	0.254 m

Centre of buoyancy (aft of nose), L_{CB}	0.4621 L_{OA}
Volume of displacement, ∇	0.508 m^3
Wetted surface area of bare hull, S_{WA}	5.988 m^2

2.2 Computational Domain and Boundary Conditions

In the numerical simulations, computational domain and mesh sizes are adjusted according to model length which is L=4.356 m. The computational domain is generated according to the guideline published by the ITTC (2011) and it extends for 3L in front of the submarine, 9L behind the submarine, and 4L to the side and 4L to the under the submarine. The distance above the submarine model is 2L. The flow around the submarine is considered symmetric with respect to centerline of the hull, therefore only half of the computational domain was modeled and computational time is reduced more than half.

Figure 5 illustrates that the flow is given from 'velocity inlet' and the end of the computational domain is defined as 'pressure outlet' boundary condition. The top and bottom boundaries and the submarine are defined as 'wall'. In order to reduce computational complexity and solution time, only half of the domain and submarine is modelled, since for this condition the flow is assumed to be symmetrical with respect to the longitudinal horizontal and vertical planes. This is acquired by using 'symmetry plane' boundary condition that enables to accurately simulate the other half of the computational domain.

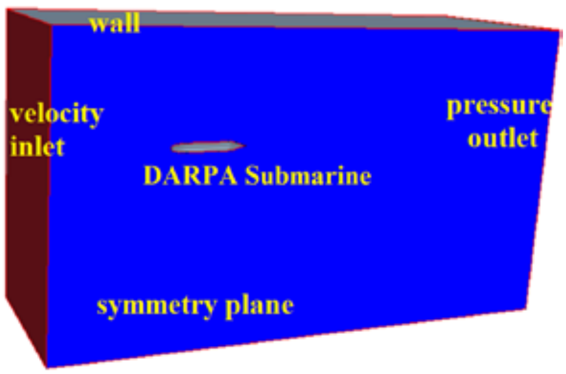

Figure 5. Boundary conditions of the computational domain for DARPA Suboff Submarine.

The submarine is considered as totally submerged which means that the free surface effects are neglected.

2.3 Grid Generation

The grid generation techniques used for the CFD simulations are summarized as follows: The numerical mesh is a structured grid; however, the mesh is composed of unstructured hexahedral cells on the submarine. Prismatic cells are applied to near the surface of the submarine for resolving the boundary layer, and local volume mesh refinements around the submarine were utilized, in order to capture the turbulence effect with high resolution.

In the analysis, the first grid point from the wall, the y^+ value was sufficiently small for the turbulence to be captured in the boundary layer. The wall y^+ value is $y^+ \leq 5$ in the simulations.

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The wall y^+ value ranges in the simulations for V=3.046 m/s and V=9.255 m/s are presented in the Figure 6 and Figure 7. The y^+ values are between 0.0798 and 1.45 for V=3.046 m/s simulations and 0.123 and 3.74 for V=9.255 m/s simulations.

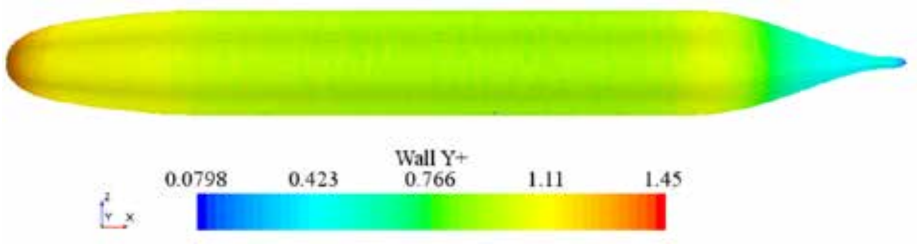

Figure 6. Wall y^+ distribution on the surface of submarine for V= 3.046 m/s.

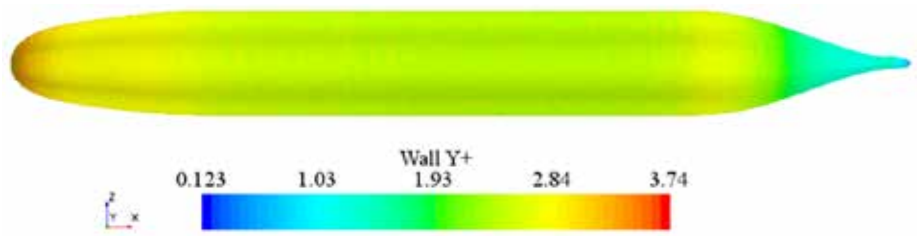

Figure 7. Wall y^+ distribution on the surface of submarine for V= 9.255 m/s.

In the numerical analysis, the other main parameter ensuring the stability is time step. Time step (Δt) defines the time of each iterative solution and it is determined as 0.01 s for all of the cases which are carried out in the study.

Mesh over the computational domain and near the submarine model, especially in boundary layer region are presented by Figure 8 and Figure 9, respectively.

In conclusion, the total number of elements i.e. the mesh number is approximately 1.26 million for the whole computational domain. This grid is called in the paper as ''Medium Grid''.

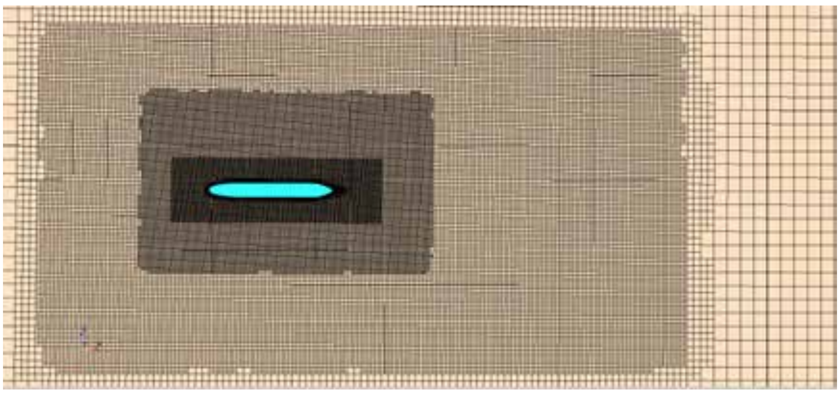

Figure 8. Grid structure over the computational domain.

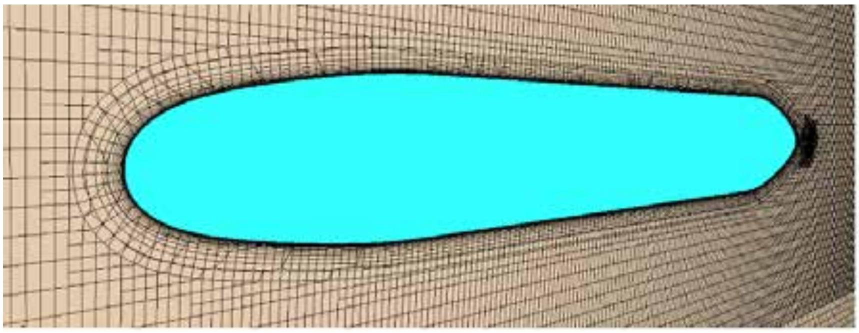

Figure 9. Grid structure in boundary layer region.

2.4 Numerical Models and Flow Conditions

3-D turbulent flow is modeled with the models of segregated flow and constant density. Implicit unsteady is accepted for the physical time in the simulations. Reynolds Averaged Navier-Stokes (RANS) model with k-Ɛ turbulence model was utilized to solve the governing equations. The analyzes were made in a single phase, so the free surface effect and wave resistance was neglected. Since the water temperature in the experiments is unknown, the temperature is accepted as 20 C° and the water properties is generated for this temperature.

In this study, the experimental cases of DARPA Submarine is used as a benchmark case and the simulations are carried out for the flow velocities velocities of V_1= 3.046 m/s, V_2= 5.144 m/s, V_3= 6.091 m/s, V_4= 7.161 m/s, V_5= 8. 231 m/s and V_6= 9. 255 m/s. All of the other parameters such as mesh, turbulence model, flow properties etc. are kept as constant in the simulations.

3. Resistance Predictions and Numerical Uncertainty Analysis

3.1 Validation of the Resistance Predictions

The total resistance (R_T) values of the submarine model for 6 different velocities (V_1= 3.046 m/s, V_2= 5.144 m/s, V_3= 6.091 m/s, V_4= 7.161 m/s, V_5= 8. 231 m/s and V_6= 9. 255 m/s) have been obtained numerically and compared with the experimental results. Table 2 shows the comparison of the experimental results and CFD predictions of the resistance values.

Table 2. Comparison of the experimental results and CFD predictions of total resistance values.

V (m/s)	R_T [N] Experiment	R_T [N] CFD (Medium Grid)	Difference (%)
3.046	87.40	86.60	0.91
5.144	242.20	234.96	2.98
6.091	332.90	322.31	3.18
7.161	451.50	437.90	3.01
8.231	576.90	562.03	2.57
9.255	697.00	678.80	2.61

According to the comparison of the experimental results and CFD predictions of resistance values, the difference between the experimental and CFD values are in the range of 0.9 % and 3.2 %. When the total resistance of the experimental and numerical values are compared, it can be said that the total resistance values obtained by CFD are similar to those of the experimental results.

The following sections of the study is performed using the same CFD approaches and models which are used for the flow simulations around the DARPA Submarine.

3.2 Numerical Uncertainty Analysis

In this part of the study, uncertainty analysis are conducted for the assessment of Grid Convergence Index (GCI), which is based on the grid intensity in the computational domain, recommended by the ITTC (ITTC, 2011). All of the theoretical background of the grid uncertainty analysis performed in this paper is based on the studies from the literature Stern et al. (2006), Celik et al. (2008).

In the study, only the grid dependent uncertainty is calculated. Time dependent uncertainty is neglected since the time step is kept constant (Δt =0.01 s).

The grid convergence study is conducted using the results of the three simulations in which the grid size was systematically coarsened in all directions while keeping all other input parameters (such as time-step) constant. Number of the mesh cells for coarse, medium and fine grids are tabulated in Table 3.

Table 3. Number of cells for the numerical uncertainty analysis of the DARPA Suboff model submarine.

Grid density	Coarse Grid	Medium Grid	Fine Grid
Number of cells	590263	1260443	2812624

Uncertainty assessments are carried out for the total resistance predictions for 3 different cases of V=3.046 m/s, which has the lowest velocity, V=6.091 m/s, which has the medium high velocity and V=9.255 m/s, which has the highest velocity value. One of the reasons for choosing the case of V=6.091 m/s is that the highest difference between experimental and numerical results (3.12 %) is obtained at this speed value, as it is shown in Table 2.

The results of the resistance values with the experiment and the numerical results for coarse, medium and fine grids are presented in Table 4.

Table 4. Comparison of the experimental results and CFD predictions of total resistance values.

V (m/s)	**R_T [N] CFD (Coarse Grid)**	**R_T [N] CFD (Medium Grid)**	**R_T [N] CFD (Fine Grid)**
3.046	84.64	86.60	87.78
6.091	318.36	322.31	324.90
9.255	673.26	678.80	700.20

The uncertainty analysis is performed by using the total resistance values given in Table 4. The total numerical uncertainty values obtained by grid convergence study are presented in Table 5.

Table 5. Total numerical uncertainty values obtained by grid convergence study.

V (m/s)	**U_T (%)**
3.046	1.025

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6.091	1.89
9.255	1.33

The total uncertainty is calculated in the range of 1-2 %, hence it can be said that the numerical stability is ensured in the simulations. The approaches and models utilized in the study, especially RANS with K-Ɛ turbulence model gave fairly similar predictions comparing with the experimental results.

4. Flow Simulations around Shark Inspired Submarine Model

4.1 Geometry

In this section, the generated nature-submarine model is introduced. The submarine form is generated using a great white shark geometry. The great white shark is known for its size that can exceed 6 m in length and 2240 kg in weight. A mature great white shark can swim as fast as 40km/h (Url-6). This is one of the reasons to be selected as the inspired model. Its body is perfectly adapted to a life of predation.

A real great shark and a 3-D model of the great shark generated used in this study are presented in Figure 10.

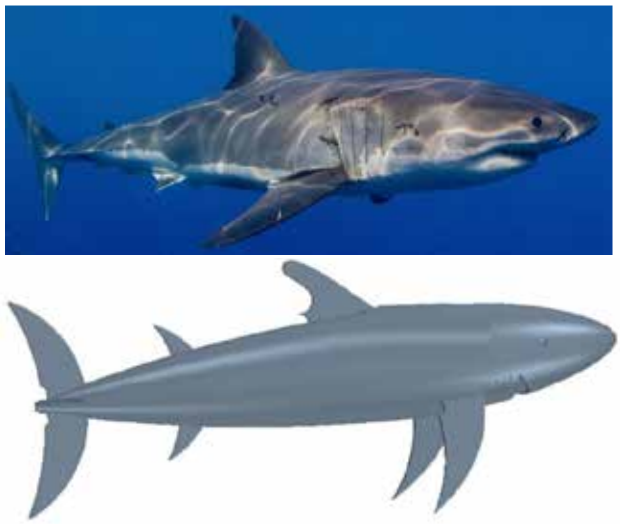

Figure 10. A real great shark (Url-5) and a 3-D model of the great shark.

4.2 CFD Simulations

In this section, CFD study for the newly generated submarine model for the investigated cases and total resistance results for the same conditions are presented. The same meshing techniques and computational models are used to perform the simulations of the shark inspired submarine with the DARPA Submarine simulations.

Geometry of the shark inspired submarine form is created reducing the tail and flipper parts of the 3-D model of the great shark shown in Figure 10. Dimensions of the form are set same as possible with DARPA Submarine model. The length of the submarine inspired model is 4.36 m, which is as the same as the length of the DARPA submarine model. The average breadth of the submarine form is also equals to the breadth of the DARPA Submarine. 3-D geometry and mesh around the shark inspired submarine model are presented in Figure 11 and Figure 12, respectively.

Figure 11. 3-D CAD model of the Shark inspired submarine model.

The number of cells of the generated grid is approximately 1.15 million, using the mesh models and approaches applied generating the ‘’Medium Grid’’ in the simulations of DARPA submarine.

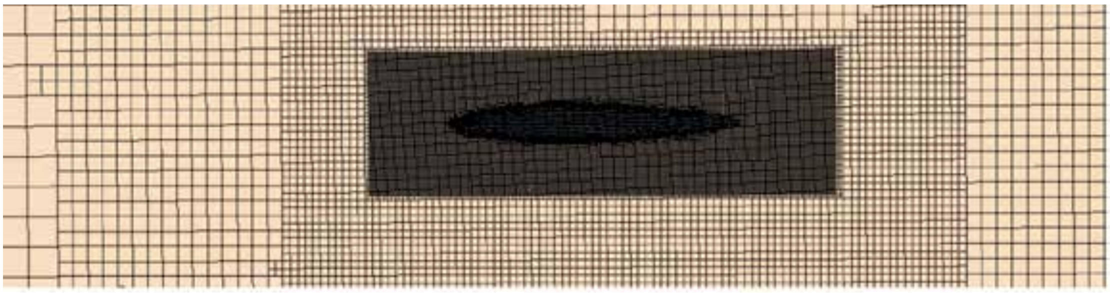

Figure 12. Mesh around the shark inspired submarine model.

4.3 Comparison of the Total Resistance Values

Resistance analysis are performed for the velocity range of 3.046 m/s and 9.255 m/s which is the same as with the DARPA submarine. Total resistance values of DARPA Submarine for ‘’Medium grid’’ conditions and Shark inspired submarine are presented by Figure 13.

When the results are compared, it is seen that the total resistance values of the Shark inspired submarine are higher than the DARPA submarine, for all of the investigated cases.

Looking at the results in more detail, for the case of V=3.046 m/s, the difference is about 20.5%. For the other cases investigated in the study (V= 5.144 m/s, V=6.091 m/s, V=7.161 m/s, V=8.231 m/s and V=9.255 m/s), the differences are in the range of 10-15%, which means that the shark inspired form has produced 10-15 % higher total resistance.

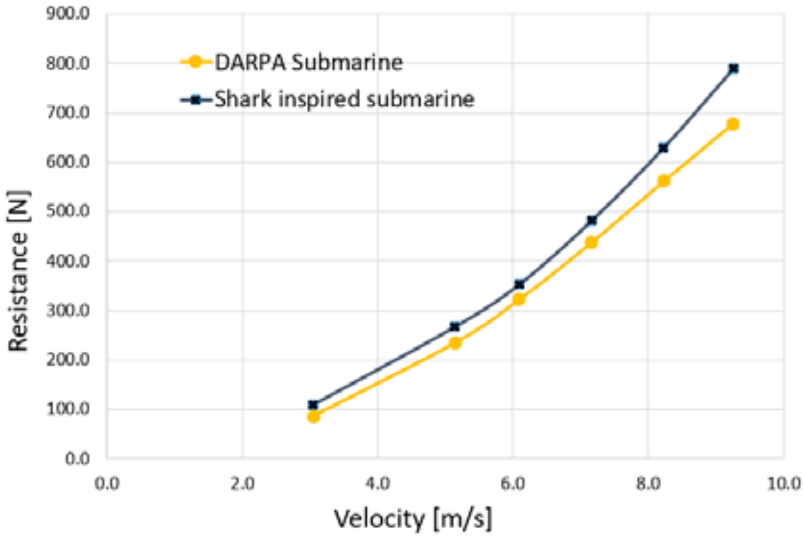

Figure 13. CFD results of the total resistance values for DARPA Submarine and Shark inspired submarine models at the velocity range of 3.046 m/s and 9.255 m/s.

5. Conclusions

This study firstly focuses on the numerical prediction of resistance characteristics of a benchmark submarine model, DARPA Suboff, for different velocity conditions. The total resistance characteristics of the submarine model is numerically obtained utilizing RANS with k-Ɛ turbulence model. The numerical results are validated with available experimental data and verified by GCI method, which is based on grid convergence. After that, a new submarine form is developed by inspiring from the nature, a 3-D model of the great shark. The resistance characteristics of the shark inspired submarine and DARPA Submarine model were compared in terms of total resistance. For the same hydrodynamic conditions and investigated velocity range, total resistance values of the shark inspired submarine are higher than the DARPA Suboff model.

Consequently, this study shows that CFD can be used as a practicable and feasible tool in gaining insight into the various hydrodynamics problems and generating new designs inspired from the nature. Although the total resistance values of the newly generated shark inspired submarine model are higher than a real submarine model, this study may bring a new perspective for new submarine forms to be developed inspiring from the nature. Much more feasible submarine designs can be generated inspired by the forms of different marine animals such as sharks or various fish species in the future.

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