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The effect of appendages on the hydrodynamic characteristics of an underwater vehicle near the free surface

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ABSTRACT

An underwater vehicle typically has various appendages such as sail, rudders and hydroplanes. These appendages affect the hull hydrodynamic characteristics, including the resistance components and the form of the generated wave due to the motion of the vehicle near the free surface. The effect of the appendages on the hydrodynamic characteristics of an underwater vehicle near the free surface is studied. Initially the DARPPA SUBOFF submarine without the appendages is selected and hydrodynamic characteristics, including the friction resistance, viscous pressure resistance, wave resistance and shape of the created wave on the free surface are calculated for Froude numbers in the range of 0.128–0.84 and non-dimensional submergence depths 1.3, 2.2, 3.3 & 4.4. Then, by adding the appendages and comparing these two conditions, the effect of appendages is obtained. The results of computations indicate that the appendages cause a mean increase of about 16% in the total resistance. This increment is due to viscosity of fluid and also the interaction of the main hull with the appendages. There are no significant changes in the wave pattern and wave making resistance due to the presence of appendages.

1. Introduction

Underwater vehicles are manned and unmanned vessels that are designed to operate at various depths of water. They may also operate at or near the free surface in some situations such as the snorkeling condition for a submarine and using GPS for an AUV. The hydrodynamic properties of an underwater vehicle moving at or near the free surface are different due to wave formation on the free surface of water. The formation of waves has various effects such as increasing the resistance of the vehicle. The wave formation may be used to detect the vehicle.

An underwater vehicle consists of several parts with various functionalities, such as pressure hull, main ballast tanks and free flooding areas. All of them are covered by an envelope which is called hydrodynamic hull to form a free stream body. The hydrodynamic hull may also be called the main hull of the vehicle. The main hull is normally attached with several control surfaces and a sail. These are called the appendages of the vehicle. The control surfaces have the functionality to provide sufficient maneuverability for the vehicle, and the sail is used to accommodate the masts, snorkeling and detecting equipment. The appendages may affect the hydrodynamic properties of the main hull, such as resistance and the shape of the generated wave on the free surface.

Weinblum [1,2] has conducted several experiments to study the effects of some parameters such as geometry, submergence depth and Froude number on resistance of submarines. Hoerner [3] has continued the parametric study of Weinblum and concluded that when a submarine is moving in a depth five times more than its diameter, wave resistance can be ignored. There are also some more experimental studies on the resistance of submarines such as Vine [4], Mackay [5] and Wilson-Haffenden [6].

Considerable literatures exists on analytical approach based on potential flow regarding the calculations of the wave resistance of marine vehicles. Bertram [7,8] has applied BEM based on potential flow theory to find the wave resistance in snorkeling and surfaced conditions of an underwater vehicle. Gourlay and Dawson [9] have used the source panel method for calculating the potential flow around the near-surface submarine.

The potential flow approach only provides a solution for the wave making resistance. The resistance due to the viscosity and consequently, the total resistance of a marine vehicle cannot be obtained by this approach. The Reynolds Average Navier Stokes (RANS) model may also be applied to compute the resistance and the other maritime hydrodynamic problems. Application of RANS to solve the marine problems goes back to Wilson et al. [10] who have obtained unsatisfactory results. By the increasing growth of

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Table 1
Principal particulars of $\lambda = 2.8$ scale of SUBOFF.

Length	Diameter	Bare Hull Surface Area	Full Appended Surface Area
1.55 m	0.18 m	0.764 m^2	0.809 m^2
Sail Length	Sail Height	Astern hydroplane Length	Astern hydroplane Height
131 mm	73 mm	71.5 mm	61 mm

Table 2
Principal particulars of $\lambda = \frac{1}{5}$ scale of SUBOFF.

Length	Diameter	Bare Hull Surface Area	Full Appended Surface Area
21.87 m	2.54 m	149.7 m^2	158.6 m^2
Sail Length	Sail Height	Astern hydroplane Length	Astern hydroplane Height
1.84 m	1 m	1 m	0.845 m

computing capacities and recent progress in RANS models, remarkable advances in this field are achieved. Nowadays, CFD is a crucial tool for various aspects of marine vehicle hydrodynamics such as resistance, propeller performance and maneuverability, not only for research but also as a design tool. More information regarding this field can be found in Hajivand and Mousavizadegan [11], Dantas and de Barros [12] and Howan Kim et al. [13].

Wilson-Haffenden [6] has calculated the total resistance of the DARPA SUBOFF submarine model with its components. He has applied ANSYS CFX software to analyze the DARPPA SUBOFF without appendages near the free surface. Liu et al. [14] have calculated the generated wave spectrums from hulls of some submarines and compared them with those of whales moving near the free surface. They indicate that these spectrums can be used to track and to position the submerged body stealthily. Nematollahi et al. [15] studied the interaction between an axisymmetric underwater vehicle and the free surface by using ANSYS CFX.

Almost all the studies in this context are on bare hulls without the presence of appendages. The effects of various appendages on resistance of two SUBOFF model submarines are studied using CFD computation. The computations are done by Star CCM+ CFD software. The resistance, its components and the form of the waves on the free surface of the water are obtained for the submarines with and without appendages. Two submarines are selected in order to study the scale effect and the influence of different regime of the flow around the hull and appendages. The first submarine is scaled down to $\lambda = \frac{L_s}{L_m} = 2.8$ of SUBBOF. This scale is selected because its experimental results are available. The dimensions of this model are given in Table 1. The second submarine is scaled up to $\lambda = \frac{L_s}{L_m} = \frac{1}{5}$ of SUBBOF with the dimensions given in Table 2. This scale ensures that the flow around the appendages is turbulent. The Reynolds number for the sail and hydroplanes is about 1.87×10^6 for the large scaled model. The length of the larger model is 21.87 m which is almost equal to the size of a midget submarine. The submarines are attached with a sail at parallel middle body and four control surfaces at the aft body of the main hull. The submarine model with all appendages is shown in Fig. 1. The complete geometrical properties of the SUBOFF submarine may be obtained in Groves et al. [16].

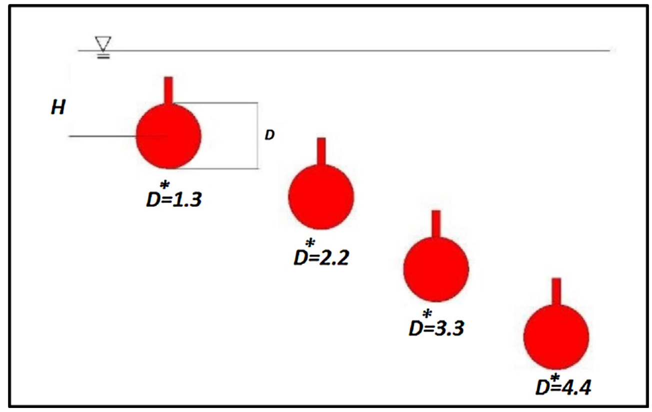

Fig. 2. The submergence depth of the submarine models.

The computations are done at different depths of submergence for both models. A non-dimensional submergence depth parameter is defined by $D^* = \frac{H}{D}$, where H is submergence depth and D is the submarine diameter. The model with $\lambda = 2.8$ is analyzed at $D^* = 1.3$, 2.2, 3.3 & 4.4 as shown in Fig. 2 and the model with $\lambda = 1/5$ is analyzed at $D^* = 1.3$. The flow velocity is considered so that the Froude number is in the range of 0.128–0.84 for both models.

2. Fluid flow modeling

The resistance of the marine vehicles is an interaction with the surrounding environment. The marine vehicles such as submarines are surrounded by water and air above the water surface. The flow of the water around the main hull and appendages, and also the effect of the air above the free surface should be analyzed to obtain the resistance of the submarine and its components. The viscous flow around a submarine is modeled by the Navier Stokes equations. Navier-Stokes equations are used for both laminar and turbulent flow. The application of Navier-Stokes equations in solution of the fluid flow is called direct numerical solution (DNS). It is necessary to use very fine meshing to capture all the turbulence effects for a turbulent flow regime in DNS. The Reynolds-averaged Navier Stokes (RANS) equations can also be applied to model the turbulent flow.

RANS equations are the time-averaged Navier-Stokes equations through assumption that the fluid flow parameters are composed of a time average part and a fluctuation part, i.e. $u = \bar{u} + u'$, $p = \bar{p} + p'$ where $\bar{u}, \bar{p}$ are the time-averaged and u', p' are the fluctuation velocity and pressure, respectively. RANS equations may be given as follows for an incompressible flow [17]:

$$\frac{\partial(\rho\bar{u}_i)}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho\bar{u}_i\,\bar{u}_j + \rho\overline{u_i' u_j'}\right) = \frac{\partial\bar{p}}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right)\right) \quad (1)$$

$$\frac{\partial(\rho\overline{u_i})}{\partial x_i} = 0 \quad (2)$$

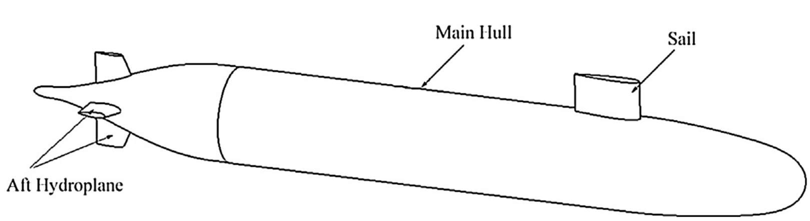

Fig. 1. The SUBOFF submarine with its appendages.