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How does the free surface affect the hydrodynamics of a shallowly submerged submarine?

Mojtaba Maali Amiri*, Paulo T. Esperança, Marcelo A. Vitola, Sergio H. Sphaier

Ocean Technology Laboratory (LabOceano-COPPE), Federal University of Rio de Janeiro, Rio de Janeiro, RJ 21941-907, Brazil

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ABSTRACT

It has long been recognized that a shallowly submerged submarine traveling beneath the free surface experiences a larger resistance force in conjunction with a lift force and a pitch moment, which all vary periodically with respect to Froude number. As is well known, the periodic behavior of the forces and moment mainly has to do with the interference effects between the dominant wave systems inside the submarine wake, which predominantly originate from the bow, stern and shoulders. In naval architecture, the principal type of interference is typically considered between the bow and stern waves, where the geometry undergoes abrupt changes. However, as the aft shoulder of a shallowly submerged submarine operates in a closer proximity to the free surface compared to the stern, it is surmised that interference between the bow and aft shoulder waves may have a more significant effect on the behavior of the forces and moments. Accordingly, the main purpose of the present study is to investigate whether the interaction between the bow and aft shoulder waves or the interaction between the bow and stern waves has a more dominant effect on the hydrodynamic behavior of a shallowly submerged submarine. In this regard, the straight-ahead simulations of a generic submarine with constant forward velocities are performed in commercial code STARCCM+ using URANS equations with a Reynolds stress turbulence model at submergence depths and Froude numbers ranging from $h = 1.1D$ to $h = \infty$ (D: submarine diameter) and from $Fn = 0.205$ to $Fn = 0.512$, respectively. The numerical model is partially validated against the existing experimental resistance force data. The analysis of the obtained results demonstrates that in case of the shallowly submerged submarines, the interaction between the bow and aft shoulder waves has a dominant effect on the behavior of the resistance force, lift force and pitch moment.

1. Introduction

The standard equations of motion proposed by Gertler and Hagen [1] for submarine maneuvering simulations is considered as the first official model to simulate the maneuvering of submarines in six degrees of freedom. In this mathematical model, the hydrodynamic forces and moments are expressed in terms of hydrodynamic coefficients, which are obtained through performing relevant static and dynamic tests [1]. The model is originally developed for submarines far from free surface and seabed.

After the development of the model proposed by Gertler and Hagen [1], there has been a notable surge toward modifying this mathematical model to account for several effects, such as the effect of vortex shed from sail [2], the effect of propeller slipstream [3] and even recently the effect of the free surface [4]. In this regard, the assessment of the free surface effect on the hydrodynamics of a shallowly submerged submarine has received an increasing attention in hydrodynamics [5–11], which can be associated with an increase in the strategic requirement for naval submarines to operate in near surface and littoral environments.

A clear consequence of a submarine moving close to the free surface is the generation of surface gravity waves that are stationary with respect to the submarine hull. These gravity waves are the direct result of the interaction between the dynamic pressure distribution along the submarine hull and the flexible free surface, which for a deep-water environment leads to the creation of a wave system that closely resembles the classical Kelvin wave pattern.

The energy required for the creation of this wave system causes an increase in the axial resistance force of a shallowly submerged submarine [12–14]. The length based Froude number defined as follows governs the resistance force due to the wave system:

$$F_n = \frac{U}{\sqrt{Lg}}, \tag{1}$$

where U indicates the submarine velocity and L the submarine length and g the gravity acceleration.

* Corresponding author.
E-mail address: mojtabamaali@oceanica.ufrj.br (M.M. Amiri).

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However, besides the wave-making resistance force, a shallowly submerged submarine experiences a lift force and a pitch moment. This has been indicated in previous researches, such as Broglia et al. [5], Jagadeesh and Murali [6], Dawson [7], Mansoorzadeh and Javanmard [8], Nematollahi et al. [9], Carrica et al. [10] and Salari and Rava [11], where numerical and experimental methods have been used to investigate the free surface effect on the hydrodynamics of shallowly submerged underwater vehicles.

In this regard, Broglia et al. [5], Jagadeesh and Murali [6], Mansoorzadeh and Javanmard [8], Nematollahi et al. [9], Carrica et al. [10] and Salari and Rava [11] evaluated the hydrodynamic characteristics of underwater vehicles traversing beneath the free surface at different submergence depths and Froude numbers, using RANS equations with various one-equation and two-equation based turbulence models. To validate the numerical results, the experimental data of the forces and moments acting on the same body used in the simulations is employed. Generally, the results obtained from these studies show that a submarine traveling close to the free surface experiences a larger resistance force along with a lift force and a pitch moment. The results further reveal that the resistance force, lift force and pitch moment all are functions of both Froude number and submergence depth.

Another noteworthy study related to the subject under consideration conducted by Dawson [7], who performed experimental investigation and numerical examination (based on potential flow) into the influence of submergence depth, Froude number and length-to-diameter ratio on the interaction between a shallowly submerged underwater vehicle and the free surface. The results show that the resistance, lift force and pitch moment all vary periodically with respect to Froude number and are directly influenced by the wavelength of the free-surface wave field generated by the submerged body.

Thus, nearly all the studies mentioned above have demonstrated that an underwater vehicle moving beneath the free surface experiences a larger resistance force, together with a lift force and a pitch moment, which all vary periodically with respect to Froude number [7].

Following Newman [15] and Lewis [16], the oscillatory behavior of the forces and moments is mainly associated with the interference effects between the dominant wave systems inside the submarine wake, i.e., wave systems originating from the bow, stern and shoulders. In this regard, in naval architecture, the principal type of interference is typically considered between the bow and stern waves, where the geometry undergoes sharp changes [17,18].

On the other hand, in case of the submarine hulls, as the aft shoulder operates in a closer proximity to the free surface compared to the stern, it is surmised that the aft shoulder may contribute more to the submarine wave system. Therefore, the interference effects between the bow and aft shoulder waves may have a more significant influence on the behavior of the forces and moment acting on a shallowly submerged submarine hull.

Thus, in the present paper, to investigate whether the interaction between the bow and aft shoulder waves or the interaction between the bow and stern waves has a more dominant effect on the hydrodynamic behavior of a shallowly submerged submarine, an attempt is made to answer the following single question:

- How does the free surface affect the hydrodynamics of a shallowly submerged axisymmetric submarine geometry?

To answer this question, the hydrodynamic behavior of a submarine close to the free surface is evaluated. This evaluation can be performed numerically or experimentally.

A submarine moving beneath the free surface generates a wave system that closely affects the dynamic pressure distribution around the submarine. To clarify this, consider a submarine moving in a close proximity to the free surface. The pressure distribution along the hull generates a wave system that reciprocally affects the pressure distribution over the body.

Thus, to evaluate closely the hydrodynamics of a submarine moving beneath the free surface, the assessment of pressure distribution over the body surface (local variables) and consequently the forces (global variables) acting on the hull are necessary. This means that performing experiments requires a separate set of apparatuses to measure each local and global variable along with the characteristics of the wave system.

Moreover, during the experiments a vertical post is required to mount the model to a towing carriage in the towing tank. This requires the truncation of the model in stern region in order to accommodate the horizontal sting, which definitely affects the pressure in this region.

Therefore, in this study, to avoid high costs of performing experiments and the effect of the mounting device on local and global variables, the numerical methods are preferred over the experiment. Regarding how much additional information numerical methods provide, the usual CPU time requirement in numerical methods seems reasonable. For instance, in this study, a desktop PC, which has a 64 bit Intel Processor i7-3770@ 3.40 GHz with 16 GB of RAM, is used and each simulation takes a physical time about 70 h to complete.

Accordingly, in the current research to investigate whether the interaction between the bow and aft shoulder waves or the interaction between the bow and stern waves has a more dominant effect on the hydrodynamic behavior of a shallowly submerged submarine, the straight-ahead simulations with constant velocities are performed, using URANS equations coupled with the Reynolds stress turbulence model developed by Speziale et al. [19]. The simulations are performed in the commercial code STARCCM+ in a range of submergence depths from $h = 1.1 \times D$ to $h = \infty$ (D: submarine diameter) and body length Froude numbers from $F_n = 0.205$ to $F_n = 0.512$. The submergence depth $h = \infty$ corresponds to the totally submerged case.

To validate the numerical model, the resistance force obtained from the totally submerged simulations is compared against the experimental data found in Liu and Huang [20] and the resistance force obtained from the shallowly submerged ones is compared against the experimental data provided by Dawson [7].

The axisymmetric submarine geometry employed in this paper is the SUBOFF geometry with the general geometric characteristics given by Groves et al. [21].

In the following sections of the paper, first a short description of the characteristics of the wave system of a submarine moving beneath the free surface and the numerical model, in conjunction with the geometry and computational conditions is given. This is followed by the presentation of the computational domain and boundary conditions along with the process of grid generation. Finally, the obtained numerical results together with the process of verification and validation of the numerical model are presented.

2. Methodology

2.1. Wave system of a submarine traveling beneath the free surface

The interaction between the dynamic pressure distribution along the length of a shallowly submerged submarine and the non-rigid free surface generates surface gravity waves [7]. This wave system is a combination of several wave systems created at points along the body and probably is a function of submarine overall length, body form and advance speed.

As is well known, the positive and negative dynamic pressure peaks around the submarine hull are the main contributors to the submarine wave system on the free surface [18]. Based on the pressure distribution along the length of the totally submerged SUBOFF represented in Fig. 13, three regions, i.e., bow, stern and aft shoulder, generate the dominant wave systems inside the SUBOFF wake on the free surface. The bow and stern waves, due to a positive peak pressure, start with a crest; however, the aft shoulder wave, due to a negative peak pressure, starts with a trough.