Movement of an submerged body in conditions of shallow water depth

Abstract. Forces and moments acting on an AUV during its movement play a decisive role in its manoeuvrability and operational parameters. When choosing the shape of a vehicle, it is necessary to provide for obtaining acceptable hydrodynamic qualities that ensure the vital activity of a crew and the placement of equipment, which directly affects the dimensions and external outlines of an AUV. The purpose of the study was to determine the performance of the numerical model in the ANSYS software by comparing the results of the hydrodynamic characteristics of the object with experimental data and data from other studies. Hydrodynamic forces acted on the immersed body from the side of the liquid at a small immersion depth. The dependences demonstrated both qualitative and quantitative agreement between the experimental and numerical results. In general, we concluded that the proposed methodology and method of conducting model experiments and the numerical algorithm developed by us, accurately describes the process of motion of a submerged body in a near-surface water environment.

1 Introduction

Underwater research, emergency rescue vehicles and devices for other purposes, which are created or under development [1-2], differ significantly in external, weight and dimensional characteristics. Despite the wide variety of modern autonomous underwater vehicles (AUV), they have a common property, namely the ability to manoeuvre at various submergences from a free surface.

Forces and moments acting on an AUV during its movement play a decisive role in its manoeuvrability and operational parameters. Only the availability of complete information about the hydrodynamic characteristics of an AUV enables us to determine all the conditions under which its safe operation is possible, especially at small submergences. The external form of a AUV, even within the same class, can vary significantly, which is explained both by the nature of the tasks performed, and by technical data and design features. When choosing the shape of a vehicle, it is necessary to provide for obtaining acceptable hydrodynamic qualities that ensure the vital activity of a crew and the placement

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of equipment, which directly affects the dimensions and external outlines of an AUV. Divsalar [3] conducted a numerical study of the hydrodynamic performance of AUV using the computational fluid dynamics method, taking into account the shape of bow and stern and length-to-diameter ratio (LTDR). He considered three different shapes of bow models, namely a conical one, a hemispherical one, and a bullet-shaped one. The results obtained were compared with the data for the DARPA SUBOFF submarine hull described in the scientific literature [4]. Based on the DARPA ZUBOFF model, three different tail models were created, namely a conical one, a sharp one, and a hemispherical one. Taking into account the influence of the LTDR and the shape of bow and stern ends on hydrodynamic coefficients, it was concluded that the shape of the hull with a bullet-shaped bow and a sharp stern with LTDR equal to 7.14, worked better than the DARPA SUBOFF model. Friedman [5] found that there was a range of LTDR that was suitable for achieving minimum resistance. Kormilitsin and Khalizev [6] demonstrated that when testing submerged bodies of various geometric shapes, the minimum resistance at a large submergence of $h_{sub}$ ($h_{sub}$ is the distance from the free water surface to the axis of symmetry of a submerged body) occurred approximately at LTDR equal to 6.5. However, the placement of units and crew were impractical in a submarine hull in the form of a body of rotation of the power plant. As a result, the shape of the AUV hulls, as a rule, had a parallel mid-body section of considerable length, necessary for the placement of onboard systems, which was more effective than changing the profile of the bow and stern ends of a vessel. The approach is implemented in the hull design of modern submarines, and the placement of a parallel mid-body section increases LTDR above the optimal value of equal to 6.50.

Also, for safe navigation, especially in a near-surface water environment, a vehicle must be reliably stabilized in all modes of movement. The study [7] solved the problem of unsteady turbulent flow around a maneuvering ship, which was applied to a model problem concerning the extreme case of submarine maneuvers. Holloway et al. [8] considered the problem of flow separation from 3 slender bodies of revolution in steady turning is studied using Computational Fluid Dynamics RANS simulations. This study [9] presents computational and experimental studies of an AUV undergoing prescribed lateral and angular acceleration manoeuvres (pure sway and pure yaw).

A variety of different requirements for designed vehicles enables us to give general recommendations only in terms of choosing a streamlined axisymmetric shape, because the geometry of a submerged body is related to hydrodynamic forces. Based on modelling and numerical experiments and taking into account the submergence and speeds with which modern AUVs moved during near-surface operation, Dawson [10] concluded that the effect of wave resistance $R_w$ was secondary. The vertical lift force $F_z$ and the hydrodynamic moment $M_Y$ acquired the greatest operational significance, which decreased with increasing submergence.

Despite the high interest in studies of this kind, the determination of the hydrodynamic characteristics of an AUV moving near a solid surface has not been sufficiently studied. In a number of studies, the movement of an AUV near the hull of surface [11] and underwater vehicles [12-13] was considered, the nature of their interaction was investigated. The study of a submerged body motion near the lower surface of an ice cover of various thicknesses was a separate direction [14-16]. However, the problem of a submerged body motion under conditions of a limited bottom depth may be of particular practical interest. In the study [17], a viscous flow was calculated to predict the effect of bottom clearance on the hydrodynamics of submarines of the Walrus class at large submergence depths. The data obtained are in good agreement with the experimental results and pointed out that the bottom gap has a strong nonlinear effect on the vertical force and pitching moment. The purpose of the study was to experimentally and theoretically determine the effect of the
water area depth on the wave resistance, vertical lift force and hydrodynamic moment acting on a submerged body from the liquid side at low submersion depth.

2 Description of the experimental setup and methodology for conducting a model experiment

2.1 Shape of models of a submerged body

During the experiments, a model of an axisymmetric submerged body with a parallel mid-body section and a LTDR equal to 8.4 was used with the overall length $L_m=1.154 \text{ m}$. Figure 1 shows the scheme of the model. The value of the mid-frame completeness coefficient was equal to $\beta=0.785$. The value of the prismatic coefficient was $C_p=0.857$. Modelling the turbulent flow regime in a boundary layer was carried out using artificial turbulators in the form of Hama strips. The turbulators were located at a distance of $0.05L_m$ from the bow perpendicular of a model and provided the sufficient level of a stable turbulent flow with a minimum increase in resistance [18].

![Fig. 1. Lines plan of the model of a submerged body](image)

2.2 Selecting the type of a towing system

To experimentally determine the forces and trimming moment acting on a submerged body, towing tanks or wind tunnels were used. To simulate the movement of a body model in a water environment in towing tanks, researchers used a towing carriage to which one or two vertical posts were attached. The model could be attached directly both to the vertical posts and through a horizontal sting connecting the vertical posts to the stern (see Fig. 2(a)) [19]. When performing experiments in wind tunnels, researchers used a horizontal bar, which could be placed both inside a model and in a stern end, to place models of submerged bodies (The model could be attached directly both to the vertical posts and through a horizontal sting connecting the vertical posts to the stern (see Fig. 2(a)) [19]. Fig. 2(b)) [19]. The posts that hold the bar had special aerodynamic fairings, which minimized the effect of interference during free-stream flow around a model and its subsequent visualization. The main disadvantage of the traditional approach to model testing is the inevitable influence of vertical posts and the presence of the bar, the ratio of its diameter to the diameter of the model body and the reduction in a body length at a stern end. A decrease in the area of the wetted surface of a hull and a change in the pressure field in a stern resulted in a change in resistance. Studies [10, 19], using numerical and experimental simulations, demonstrated that the influence of the described factors resulted in a 20% decrease in the obtained data. In addition, to prevent a model yawing, the entire structure must be sufficiently rigid.
The short length of the ice tank enables us to use a cable towing system to move models. The system has certain advantages over the traditional method of towing submerged bodies. The use of a steel cable eliminates the influence of vertical post mounting, which connects the model to the towing carriage, on the wave generation pattern.

Since the model has a zero buoyancy at a given depth $h_{sub}$, when towing at a speed $u_m$ under the influence of $F_Z$, it enables us to measure the value of the vertical submergence of the body $h^*=h_{sub}+h_m$ ($h_m$ is the deviation of the model from $h_{sub}$). It is not feasible with the traditional method of towing. Determining this parameter theoretically is also extremely difficult, as it requires large computation power. Figure 3 shows the scheme of experimental determination of the value of $h^*$.

**Fig. 2.** Schematic drawing of testing a submerged body model: a – Carderock Division Naval Surface Warfare Center; b – Static Test Frame at Canadair

**Fig. 3.** Scheme for determining $h^*$ of a submerged body model (Fr=0.62): 1 – model; 2 – position of the vertical displacement sensor; 3 – line of a free water surface; 4 – line of the initial submergence of a model $h_{sub}=0.16\,\text{m}$; 5 – line of the surface disturbance of water; 6 – line of model submergence at the moment of movement; 7 – trim angle

Figure 4 shows the scheme of performing model experiments. The length of the accelerating section was $2.314L_m$, the length of the stationary section of motion was $8.035L_m$. The vertical displacement sensor for recording the profile of the rough water surface was installed at a distance of 7 m from the end wall of the tank bowl strictly above the trajectory line of a submerged body model. Opposite the waterproof window, a camera was installed to determine the value of the vertical displacement of the model $h^*$ resulting...
from the action of a vertical lift force. Four sections of the suspended bottom were installed on special vertical lifts. They simulated the specified depth of the water area $H_b$.

Fig. 4. Scheme of performing an experiment (top view): 1 – line of the beginning of model movement; 2 – line of the end of an accelerating section; 3 – line of the end of the stationary section of movement; 4 – submerged body model; 5 – displacement sensor; 6 – speed sensor; 7 – waterproof window; 8 – camera for recording the vertical movement of a model; 9 – double bottom sections

2.3 Methodology and parameters of the model experiment

At the initial stage of the experiments, we made test measurements of $h_{sub}$ at the points of the beginning, in the middle and at the end of the model motion trajectory. The tension of the towing cable at a zero buoyancy of a body model ensured the movement in the vertical direction in the middle of the trajectory by up to $1.5D_m$ ($D_m$ is the model diameter). To determine the deviation of a model from the initially set submergence, we used a waterproof window, mounted in the side wall of the tank bowl, opposite which a VLXT-50M.I machine vision video camera was installed. This camera performed video recording with a resolution of 2464×2056 pixels and a speed of up to 163 frames/s. The camera recorded the position of a model relative to a free water surface. Using the obtained high-resolution photographic image, the change in the position of a model, as it moved relative to the set submergence at the measurement point, was graphically determined.

Earlier tests demonstrated that, taking into account the parameters of an ice tank and the dimensions of a submerged body model, the most optimal relative values of a shallow bottom depth were $H_{b1}^* = H_b/D_m = 2.9$, $H_{b2}^* = 3.6$, $H_{b3}^* = 4.3$. The parameter, at which a large depth was modelled, was equal to $H_{b4}^* = 7.5$. The initially specified relative submergence of a model during the experiments was $h_1^* = h_{sub}/D = 1.16$ и $h_2^* = 1.45$. The relative speed of movement was $Fr = \frac{u}{\sqrt{gL}} = 0.3 - 0.77$ (where $g$ is the acceleration of gravity).

3 Numerical model for determining forces and moment acting on a moving submerged body

3.1 Description of the numerical model

We developed a mathematical model to simulate the motion of a submerged body in a near–surface water environment. The calculations were performed using the ANSYS 19 R2
Academic Research software package. We considered wave generation on clear water when an object with a given geometric shape moved underwater. Calculations were performed in the ANSYS Fluent module. Two models were obtained as the basis of the movement, namely the Multiphase (Volume of Fluid) model to account for two-phase cross sections and the k-ε turbulence model. The computational domain model consisted of cells in the form of hexahedra.

The mesh was superimposed taking into account the near-wall layers, using the Inflation grid function, to improve the flowability of an object in a flow. The mesh was constructed using the CutCell algorithm.

The body motion is based on the Multiphase model to take into account a two-phase medium and the k-ε turbulence model. We used the Volume fraction equation [20] to implement the Multiphase model. When studying the wave formation on the surface of a liquid from the movement of an object in a water environment, we assumed that the liquid and gaseous media were separated by clear boundaries. The numerical method of determining the volume of liquid was used for the solution. This method assumes that the phases (liquid and gas) are considered as continuous and does not allow their mutual penetration into each other. The boundary between phases was tracked by solving the continuity equation for the volume fraction of each of the phases:

$$\frac{\partial (\alpha_q \rho_q)}{\partial t} + \nabla (\alpha_q \rho_q u_q) = 0 \quad (q = \text{gas} \text{ or } \text{liquid})$$  (1)

where \(\alpha_q\) was volume fraction of the phase in the total volume; \(\rho_q\) was phase density; \(\nabla\) is nabla operator, \(u_q\) was phase velocity. The indices \(g\) and \(l\) represented gaseous and liquid mediums, respectively.

We considered two scalar parameters, namely \(k\) was turbulence kinetic energy; \(\varepsilon\) was the viscous energy dissipation rate of turbulence to determine turbulent viscosity [21]. In this scenario, the system of Navier-Stokes equations had the following form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0$$

$$\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_i} = -\frac{\partial P'}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu_{\text{eff}} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + S_M$$

where \(P' = P + \frac{2}{3} \rho k \frac{\partial u_k}{\partial x_k} \) and \(\mu_{\text{eff}} = \mu + \mu_t \)

$$\mu_t = C \mu \rho \frac{k^2}{\varepsilon}$$

$$\frac{\partial k}{\partial t} + \frac{\partial u_i k}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \mu_{\text{eff}} \frac{\partial k}{\partial x_j} \right] + P' - \varepsilon$$
\[
P_k = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} = \frac{2}{3} \frac{\partial u_k}{\partial x_k} \left( 3 \mu_t \frac{\partial u_k}{\partial x_k} + \rho k \right)
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \left( -\rho u_i u_j \frac{\partial u_i}{\partial x_j} \right) + C_{\varepsilon 2} \frac{\varepsilon}{k}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \left( -\rho u_i u_j \frac{\partial u_i}{\partial x_j} \right) + C_{\varepsilon 2} \frac{\varepsilon}{k}
\]

\[
u_{\text{Wall}} = 0
\]

\[
\rho u = \frac{\dot{m}}{\int_S dA}
\]

\[
\text{flow exit area} \quad \text{boundary between liquid and gaseous phase} \quad \text{flow entry area}
\]

\[
\text{(Static Pressure)} \quad \text{(Mass-flow-inlet)}
\]

Fig. 5. Model boundary conditions
3.2 Evaluation of the operability of experimental and numerical simulation

Despite all the advantages of a cable towing system, it is obvious that the presence of a steel cable and devices for attaching the model to it, can affect the nature of wave generation. To assess the degree of the towing cable influence on the profile of rough surface, a series of numerical calculations was performed. During calculations, we simulated parameters similar to the parameters of the model experiment (speed of movement and submergence of the model and bottom depth).

The submerged body model in the calculations was similar to the model used in model experiments. Initially, the motion of a submerged body was simulated with specified speed and submergence parameters without of a towing cable. Further, we took into account a cable and connecting devices (Fig. 7).

Fig. 7. Numerical model of submerged body No. 1 with elements for attaching a towing cable

During the calculation, we determined the profiles of the rough liquid surface and constructed the dependence of the vertical component of the pressure distribution $P$ along the lower surface of a submerged body model.

$P = \rho g h$

Figure 8 shows an example of the comparing results for the speed $Fr=0.42$.

Data analysis demonstrated that a towing cable had little effect on the data obtained. For the least favourable cases, the difference in results did not exceed 5%. Therefore, we used a model of a submerged body without a towing cable in further numerical solutions.
Fig. 8. Comparison between the dependences of the pressure distribution along the lower surface of a submerged body and the profiles of gravity waves for model No. 1 Fr=0.42: 1 - Agr*10 (model without a towing cable); 2 - Agr*10 (model with a towing cable); 3 – CP (model without a towing cable); 4 – CP (model with a towing cable)

We compared the experimental data obtained during the towing of model No. 1 (h* = 1.16) and the results of numerical simulations with the known data of model experiments. For comparison, we used the profiles of gravity waves obtained when towing the DARPA SUBOFF model having a relative elongation Lm/Bm = 8.5 and φm = 0.815 at a relative submergence h* = 1.02, published in Dawson’s study (2014) (Fig. 9).
Fig. 9. Comparison of gravity wave profiles obtained at $Fr=0.3$ (a), $Fr=0.5$ (b): 1 – model No. 1 experiment; 2 – Dawson’s experiment (2014); 3 – model No. 1 numerical calculation

The analysis of the profiles demonstrated a fairly good agreement between the data of Dawson's experiments and the model experiments obtained in the study. Figure 9 shows the dependencies $A^* = A_{gr}/L_{m}$ at $Fr=0.3$ and $Fr=0.5$. The difference in the height of gravity waves can be explained by the difference in the hull shape and the relative depth of the models. Also, curve 2 of Fig. 9b demonstrated the effect that the system of attaching a model to a towing cart in the form of a vertical post had on the wave pattern formed at the stern end of the model during the Dawson’s experiments.

Unlike Dawson’s study (2014), the authors had no equipment that would enable them to take experimental measurement of the forces and moment acting on a submerged body during its movement. For this reason, to compare the obtained results of the values of the coefficients $C_R$, $C_F$, $C_M$ we used the data of numerical calculations of the motion of model No. 1 and compared them with the experimental results of Dawson (Fig. 10-11).

We concluded that the results agreed qualitatively. The $C_R$ dependencies in both scenarios had two local maxima. The first maximum was at $Fr=0.3$ and the second one obtained in Dawson's experiments was at $Fr=0.5$, in the authors’ numerical calculations was at $Fr=0.5$. The $C_R$ values were similar.
Fig. 10. Comparison of CR dependencies: 1 – Dawson’s experiment (2014); 2 – model No. 1 numerical calculation

Fig. 11. Comparison of $C_F$ dependencies: 1 – Dawson’s experiment (2014); 2 – model No. 1 numerical calculation
Dependences of the CM coefficient also had similar values, including the nature of the location of the local maximum at Fr=0.33. A local minimum, as for the CR dependences, according to the results of Dawson, was observed at Fr=0.5, and as for the authors’ results it was at Fr=0.45.

Fig. 12. Comparison of CM dependencies: 1 – model No. 1 experiment; 2 – Dawson’s experiment (2014); 3 – model No. 1 numerical calculation

The dependences demonstrated both qualitative and quantitative agreement between the experimental and numerical results. The difference in the values and shapes of the curves can be explained by various parameters of the submerged bodies and by the methods of towing models and the degree of their influence on the results obtained.

In general, we concluded that the proposed methodology and method of conducting model experiments and the numerical algorithm developed by us, accurately describes the process of motion of a submerged body in a near-surface water environment.

4 Conclusion

Using the ANSYS Academic Research software package, a numerical model was developed that enabled us to analyse wave generation when a submerged body moved near a water free surface; to determine the values of forces and hydrodynamic moment acting on a submerged body when it moved in a near-surface water environment at different speeds under conditions of a limited bottom depth. The operability of the numerical model was confirmed by comparing the obtained theoretical results with the data of model experiments.

We calculated pressure fields along the upper and lower surfaces of a moving submerged body and obtained dependences of the relative height of gravity waves on the number Fr for a given value of $H_b^*$ according the profiles of a rough surface.

The results of the numerical simulation demonstrated that the movement under conditions of a shallow water depth with a minimal submergence significantly increased the values of coefficients $C_W$ and $C_F-C_F^0$ compared with the data for deep water.
The velocity at which $C_W$ acquired maximum values with a decreasing bottom depth shifted to the area of lower velocities. The comparison of the results of model and numerical experiments demonstrated a qualitative agreement between the obtained dependences. The obtained experimental and theoretical results can be used in the design of AUVs to stabilize their movement in a near-surface aquatic environment, depending on the speed of movement under conditions of the limited depth of a water area.

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