Results of computer simulation of force impact of difficult marine conditions on underwater objects

Y. V. Guryev¹ and M. Z. Slutskaya²

¹ Dr. of Eng. Sc., Professor, Naval Polytechnic Institute (Branch) MESC NF “Naval Academy”, Saint-Petersburg, Russia
² Naval Polytechnic Institute (Branch) MESC NF “Naval Academy”, Saint-Petersburg, Russia

e-mail: slzmarina@rambler.ru

Abstract. The paper presents a numerical method for calculating the hydrostatic and hydrodynamic reactions of marine underwater objects moving in an arbitrary manner under conditions of internal waves and sea currents. The method is based on the theory of potential, eddy and wave currents. The effect of viscosity on hydrodynamic reactions is taken into account indirectly by introducing a special eddying system that simulates the effect of longitudinal vortices on the hull on the pressure distribution. The paper presents the results of a computational experiment are presented, which made it possible to identify both new and confirm previously obtained regularities of the influence of the object's parameters and hydrophysical conditions on the desired reactions. The developed mathematical and software tool can be recommended for use in the design of underwater objects and the creation of simulators for their dynamics.

Introduction.

The creation of underwater vessels pursued several goals, first and foremost – to ensure their stealth, but also to reduce the negative impact of weather conditions and the associated sea waves. However, the experience of operating underwater marine objects (UMO) for various purposes has shown that there are several phenomena observed at depth, which significantly complicate their control. These include an unauthorized change in depth, which manifests itself both in sharp dips and ascents, or even the ejection of an object to the surface, frequent loss of balance, difficulties in changing the horizon of movement and a number of others [1,2]. Studies have shown that their main cause is the spatiotemporal changes in the hydrophysical fields of the ocean (density, temperature and salinity), as well as the associated internal waves (IW) that arise in the seawater and have significantly larger parameters than those of surface waves.

When designing an UMO, calculating its motion in such complex hydrophysical conditions, as well as in simulators of dynamics, an operational assessment of the hydrodynamic forces and moments acting on the object is required.

An analysis of possible approaches to their determination shows that, taking into account the requirements of the speed of calculations, numerical methods based on the potential (non-viscous) flow model [3] can be effective. The paper presents one such model developed by the authors.
1. Statement of the problem of determining the hydrodynamic reactions acting on an UMO under conditions of natural internal waves and underwater currents.

Let us consider the motion of an UMO in an inviscid liquid, the density of which changes vertically. The hull of the object is an elongated body of arbitrary shape moving along an arbitrary spatial trajectory.

The density changes abruptly at the horizontal boundary (sharp pycnocline), on which regular internal waves with known parameters exist, and the underwater current vector is given. The lower liquid is infinitely deep, while the lighter upper liquid has a depth of $h_1$ (Figure 1).

It is required to discover hydrodynamic, as well as hydrostatic reactions, arising, among other things, due to a density discontinuity.

![Figure 1. Statement of the problem](image)

Internal waves arising on the pycnocline surface have the shape of a linear sinusoidal wave. A two-layer potential model of Sretensky L.N., modified for the purpose of the work and with two interfaces "air-liquid" and "liquid-liquid" was taken as a basis.

In an unperturbed state, the free surface and the interface between liquids are horizontal, but under the influence of perturbations on both surfaces, waves of relatively small amplitude surge.

New formulas were obtained for the velocity potentials $\phi_1$ and $\phi_2$ and, respectively, for the upper and lower densities:

$$\phi_1 = -\left\{\sigma^2 + ck\right\}e^{ck(y-h)} + \left\{\sigma^2 - ck\right\}e^{-ck(y-h)} + D \sin(kx + \sigma t),$$

$$\phi_2 = -\left\{\sigma^2 + ck\right\}e^{ck(y+h)} + \left\{\sigma^2 - ck\right\}e^{-ck(y+h)} + D \sin(kx + \sigma t).$$

As a result of using the assumption about the potential nature of the flow caused by the UMO, waves and currents, a unified hydrodynamic model was created in which the potential of the total flow $\Phi(X,Y,Z,t)$ (where $X,Y,Z,t$ are the coordinates of points in space and time, respectively), in accordance with the principle of superposition, can be represented as the sum of three potentials $\Phi(X,Y,Z,t) = \phi_O(X,Y,Z,t) + \phi_{BB}(X,Y,Z,t) + \phi_{IT}(X,Y,Z,t)$

where the "o", "bb" and "it" subscripts mean the physical values created by the object, internal waves and underwater currents, respectively.

All these potentials must be in accord with the Laplace equation, the boundary conditions of impermeability on the surface of the hull and the absence of disturbances at infinite.

The current generated by the hull of the UMO is modeled by a continuous layer of sources. The effect of viscosity on the pressure distribution on the hull is taken into account indirectly by introducing a special eddying system. The mathematical solution of the problem is reduced to a numerical solution of the integral equation for the intensity of sources, after which all other characteristics (such as parameters of the eddying system, fields of velocities and pressures, hydrodynamic reactions) can be calculated.
2. Main results of numerical simulation.
The computing experiment implied calculations in a wide range of changes in the shipbuilding and kinematic parameters of the UMO (draught, hull shape, translational and angular velocities, relative direction, attack and drift angles), parameters of internal waves (amplitude, wavelength) and pycnocline (difference in density of the upper and lower liquids), as well as the position of the object in relation to the pycnocline and free surface.

The force impact of a liquid with heterogeneous density during the movement of the UMO in difficult marine conditions consists of variable hydrostatic and hydrodynamic reactions. In this case, the former, when crossing the density discontinuity, can significantly (several times) exceed the latter (Figure 2). In the area of direct intersection of the density discontinuity, the most intense and multidirectional change in hydrodynamic reactions can be observed (Figure 3).

Figure 2. The relationship between the various components of hydromechanical reactions during the ascent of an object with the intersection of the density discontinuity for $\Delta \rho = 3.0 \text{ kg/m}^3$

Figure 3. Hydrodynamic axial force and trim moment when an object ascends through a density discontinuity at different $\Delta \rho$ values $\text{kg/m}^3$
An inhomogeneous velocity field of the internal waves affects all components of hydrodynamic reactions - inertial, wave and viscous, the changes of which over time are shifted in phase relative to each other (Figure 4, 5).

Figure 4. Axial force and trim moment when an object moves at a speed of 3 m/s towards a wave with an amplitude of $a = 5$ meters, a wavelength $\lambda$ of 400 meters, at zero angles of attack, drift, roll and trim.

Figure 5. Axial force and trim moment when the object moves in the direction of wave propagation.

The numerical values of the hydrodynamic reactions acting on the UMO depend on:
- the relative sizes of the object and the internal waves: with a decrease in the ratio of the length of the UMO to the wavelength, the force impact of the latter dies out (Figure 6); conversely, with an increase in its amplitude, it grows according to a law, which is close to linear (Figure 7);
Figure 6. Coefficients of maximum values of axial force and trim moment for three objects depending on wavelength

Figure 7. Dependence of hydrodynamic reactions on the amplitude of the internal wave. The object moves at a speed of 4 m/s towards a wave with a length of 800 m
- the relative direction: at values close to 90° and 270°, along with the vertical reactions, lateral (horizontal) reactions similar in value appear, which leads to the appearance of the corresponding type of oscillation (Figure 8);
Figure 8. Athwartship force and yawing moment when the object moves perpendicular to the direction of wave propagation - the position of the UMO relative to the pycnocline: when moving away from it up or down, the hydrodynamic reactions decrease, at the same time, their numerical values upon ascent to the free surface differ from those during immersion for the same distances of the UMO from the density interface (Figure 9).

Figure 9. Dependence of the axial force and the trim moment on time when the object moves above and below the density discontinuity towards a wave with a length of 800 and an amplitude of 5 meters. When moving towards internal waves (Figure 10) and beam on to the sea (Figure 11), the previously established effect of the phase opposition of the wave and hydrodynamic reactions was confirmed. At the same time, when moving in the same direction with the propagation of the internal waves (Figure 12), there is a synchronous change in time of these physical quantities, which was previously unknown.
The charts in Figures 10-12 show the internal wave profile. This profile corresponds to a point located in the middle of the hull length.

Figure 10. Axial force and trim moment when an object moves at a speed of 3 m/s towards a wave with an amplitude (a) of 5 meters, a wavelength (λ) of 400 meters, at zero angles of attack, drift, roll and trim.

Figure 11. Axial force and trim moment when an object moves perpendicular to the direction of wave propagation. The object moves at a speed of 3 m/s, with a wave amplitude (a) of 5 meters, a wavelength (λ) of 400 meters and at zero angles of attack, drift, roll and trim.
The effect of phase opposition was established experimentally by Professor Y. V. Razumeenko in Saint-Petersburg for bodies similar in shape to those studied in this work (Figure 13) and Professor E. V. Yermanyuk in Novosibirsk for a sphere.

The variance in relation to the experimental data obtained by Professor Y.V. Razumeenko ranges from 4% to 13%, depending on the geometric shape of the model and the conditions of the experiment.

The underwater current leads to a change in the magnitude and direction of hydrodynamic reactions during the curvilinear movement of the object (Figure 14). In this case, the object was moving with a translational speed ($V_0$) of 3 m/s and an angular speed of, the angles of attack and drift are equal to zero, the circulation radius ($r$) is 200 m and the underwater current propagates in the horizontal plane.
with a constant velocity ($U_{flow}$) of 0.1 m/s. In a liquid at rest, the hydrodynamic forces remain unchanged, since the motion is stationary, which corresponds to the conditions of physical experiments to test models in a circulation basin. The underwater current complicates the picture of the flow round the body and the hydrodynamic reactions become time dependent.

![Graph 1](image1.png)

**Figure 14.** Athwartship force and yawing moment when the object moves in circulation in the presence of a current

The most complex patterns of changes in hydrodynamic reactions were obtained under the combined action of internal waves and underwater currents on the UMO during its curvilinear motion, for example, in circulation. In this case, the change in these reactions is non-periodic, which is confirmed by the dependences on the graphs shown in Figure 15.

![Graph 2](image2.png)

**Figure 15.** Changes in hydrodynamic reactions during the movement of an UMO in circulation with a radius of 200 m in the field of internal waves with a length of 400 m and an amplitude of 5 m in the presence of an underwater current with a speed of 0.1 m/s
Conclusion.
The proposed method for the numerical determination of hydrodynamic and hydrostatic reactions acting on an UMO, moving in conditions of internal waves and underwater currents, allows you to quickly perform the task using personal computers. The adequacy of the numerical data is confirmed by their satisfactory matching, both qualitative and quantitative, with the results of other authors obtained by experimental and computation methods. This allows us to recommend the developed mathematical and software tool for use in the design of UMOs and the creation of simulators for their dynamics.

References
[1] Research report “NC Anomaly” “Theoretical and laboratory studies to determine the degree of influence of anomalous natural factors on mobile marine objects” 2006 NC of Russian Academy of Science, St. Petersburg
[2] Vasilyev S, Guryev Y, Razumeenko Y and Yakushenko E 2017 Dynamics and control of underwater marine objects in difficult hydrophysical conditions Proceedings of the XI International Scientific Conference “Analytical Mechanics, Stability and Control” Kazan (Russia) June 14-18, p 211-220
[3] Guryev Y, Tkachenko I 2010 Computer technologies in ship hydrodynamics. Monograph. St, Petersburg: Naval Engineering Institute, p 326