Marine propulsion study of planning small-class amphibious vehicles

M Yu Kareлина1, V V Filatov1,4, A V Klimov1, D Yu Malakhov2 and V G Sorokin3

1Department of Machinery Parts and Theory of Mechanisms, Moscow Automobile and Road State Technical University (MADI), 64, Leningradsky Ave., Moscow, 125319, Russia
2Department of Tractors and Amphibious Vehicles, Moscow Automobile and Road State Technical University (MADI), 64, Leningradsky Ave., Moscow, 125319, Russia
3Department of Materials Science and Resource-Saving Technologies, Yanka Kupala State University of Grodno, 22, Ozhezhko str, Grodno, 230023, Belarus

E-mail: 2vfilatov@gmail.com

Abstract. The authors analyze the propulsion of the planing hulls of the various small-class amphibious vehicles. The magnitude of the resistance forces depending on the movement speed is determined experimentally. For the correct formulation of experiments and their results, the study of various models of the planing small-class amphibious vehicles must comply with the dynamic similarity of the viscous friction and gravity forces. To compare planning effect provided by the design features of various amphibious models a relative measure of the hydrodynamic qualities or its inverse value can be used. In this article, numerical simulation by means of software complex is conducted to determine the hydrodynamic properties of the different planing small-class amphibious models. To verify the adequacy and accuracy of the generated numerical model, a comparison of the computer simulation results with the data of the full-scale experiment is used. Propulsion performance is compared for amphibious models with different hull contours and additional equipment.

1. Introduction
The propulsion of the planing object is largely determined by the shape of its body. Hydrodynamic quality of high-speed planing boats is obviously better than that of planing small-class amphibious vehicles due to the presence of the latter wheel arches and exposed chassis components. To determine the hydrodynamic quality of the amphibious vehicle models with different hull contours and the composition of additional equipment, one can use the basic provisions of the theory of motion of the planning surface object described in [1] and [2].

The condition of steady (uniform) translational motion of a self-propelled surface object is expressed as follows:

\[ P_e = R_t, \]

where \( P_e \) – effective thrust developed by the propeller, kN,
\( R_t \) – the value of the total (towing) resistance, kN.

Therefore, when designing the propellers of a self-propelled surface object, it is necessary to know the force of movement water resistance. It is considered that the total hydrodynamic resistance of amphibious machines \( R_b \), kN, is represented as the sum of three components:
\[ R_e = R_{fr} + R_{vortex} + R_{wave}, \]  

where \( R_{fr} \) – the frictional resistance caused by the viscosity of water, kN,
\( R_{vortex} \) – vortex resistance the shape of the hull and suspension of the car, kN,
\( R_{wave} \) – wave resistance due to the redistribution of pressure, kN.

A detailed description of the resistance forces components when moving on the water with speed \( v_w \), m/s, is presented in [3]. The value of the total resistance can be represented as follows:

\[ R_e = \zeta \frac{\rho v_w^2}{2} \Omega, \]  

where \( \rho = 1000 \text{ kg/m}^3 \) – water density,
\( \Omega \) – wetted surface area, m\(^2\),
\( \zeta \) – the dimensionless ratio of the full water resistance.

To determine analytically the values of the coefficient \( \zeta \) and the wetted surface area \( \Omega \) is an extremely time-consuming task due to the complex nature of the hydrostatic and hydrodynamic forces distribution of the amphibian on the water. The magnitude of the resistance forces to the surface objects movement depending on the speed is determined experimentally.

For the correct formulation of experiments and generalization of their results in the study of various amphibian models must comply with the dynamic similarity of the forces of viscous friction and gravity. The Froude number \( Fr_D \) characterizes the ratio of inertia forces to gravity.

The condition of transition of the surface object to the planing mode is:

\[ v_w > 3 \left(\frac{g}{\gamma}\right)^{1/3}, \]  

where \( g = 9.81 \text{ m/s}^2 \) – gravitational acceleration,
\( D \) – weight displacement, N,
\( \gamma = 9810 \text{ N/m}^3 \) – specific weight of water.

We can compare the planing effect provided by the design features of the various models by the relative criterion of hydrodynamic quality \( k_g \) or by its inverse value \( \varepsilon \):

\[ k_g = \frac{D}{R_t}, \]

\[ \varepsilon = \frac{R_t}{D}. \]

The lower the reverse quality \( \varepsilon \), the less power is required to overcome the transition mode.

Thus, having obtained in the course of experimental studies of a series of amphibious models with different configuration towing characteristics \( R_t = f(v_w) \) and the change of the trim \( \theta = f(v_w) \), we can reconstruct these graphs in relative terms, i.e. \( \varepsilon = f(Fr_D) \) and \( \theta = f(Fr_D) \). According to the data obtained, we can also determine the dependence of the towing power on the speed \( N_t = f(v_w) \) and the specific towing power on the Froude number \( N_{tsp} = f(Fr_D) \). The presence of these dependencies for the planing small-class amphibious vehicles with different hull design and additional equipment will allow us to determine the machines characteristics in first approximation at the stage of their design.

2. Problem statement

We can conduct a numerical simulation by means of software complex for the solution of a problem of the hydrodynamic properties determination of the different amphibious models [4, 5]. In conditions of limited material resources, the main advantage of computer modeling is the possibility of experiments on objects, full-scale modeling of which involves the creation of a series of samples and the use of expensive infrastructure. In our case, the simulation of test pools for full-scale models of the bodies of surface objects is made. Computer simulation also allows you to measure any parameters at any point in the computational domain. The main disadvantage of computer modeling is the cost of computing resources and time.

The solver of the software complex is based on the equations of computational fluid dynamics characterizing flow processes: the equations of continuity, state, Navier-Stokes and Euler, as well as the laws of conservation of momentum and energy. Taking into account the peculiarities of the
problem to be solved, the general equations can be supplemented with partial dependencies, taking into account turbulence, transport of substances, multiphase, etc.

For a specific problem, taking into account its features, a system of nonlinear differential equations is compiled, the solution of which is carried out by means of discretization methods. The general methodology of the numerical experiment is shown in Figure 1.

![General methodology of the numerical experiment](image)

The geometry of the object under study is given by a three-dimensional solid-state model built in the CAD-system (computer added design), including the surfaces that form the external contours of the object (planing small-class amphibious vehicles), as well as the boundaries of the movable and stationary part of the computational domain. The problem is symmetric with respect to the diametrical plane of the machine; therefore, in order to save computing resources, the motion of half of the object in the computational domain truncated by the corresponding plane is simulated.

Calculation model (preprocessing) is prepared. The formation of the computational grid (Figure 2) occurs in three stages.

At the first stage, the surface of the imported model is transformed into triangular cells (triangulation) and a surface grid is created. Then the volume grid is formed. To discretize the computational domain, a prismatic grid with cell truncation at the boundaries is used. An additional model of prismatic layers is used to improve the quality of reproduction of processes directly on the border of the object with the environment. The final step is to set the relationship between the movable and fixed grids on the model of the superimposed grid.

In the next step, structure of the physical model based on the problem to be solved is set. In our case, the physical model is formed from the following submodels: "three-dimensional", "non-stationary implicit", "Eulerian multiphase", "volume of liquid VOF", "turbulent flow", "k-omega model of turbulence", "waves VOF", "gravity" and some others. Then parametric synthesis of the physical model is carried out: the Eulerian phases are set, the type and velocity of the flow, the position of the free surface relative to the amphibious vehicle model, the freedom degree and inertial characteristics (mass and center of mass, moments of inertia) of the object under study.

Let us proceed to the definition of boundary conditions. To do this, set the types of boundaries for each of the objects of the computational environment: the model of amphibious vehicle ("wall"), the plane of entry ("speed at the entrance"), the plane of symmetry ("plane of symmetry"), as well as mobile ("superimposed grid") and fixed ("pressure at the exit") calculation areas.

The next stage of preprocessing is the choice of the solver settings – the time step and the number of internal iterations. When determining these parameters, it is necessary to ensure the convergence and the necessary accuracy of the solution of the problem.
In conclusion, the formation of the computational model will determine the list of recorded output parameters. As a result of computer simulation of amphibious models propulsion, we obtain dependences on the speed \(v_w\), m/s, the following values: movement resistance \(R_t\), N, and trim \(\theta\), \(^\circ\).

![Generated calculation grid](image)

Also the graphical plots for the parameters depending on the speed \(v_w\), m/s, can be obtained: pressure on the surface of the hull \(p_{h}\), Pa, phase speed of the environment \(v_{ph}\), m/s, free surface.

After preprocessing, initialization of the solution is made and the iterative calculation process is started. At the last stage (postprocessing) it is necessary to process the output. For each model under test, we obtain graphs of the towing power dependence on the speed of \(N_t = f(v_w)\). Also make absolute function \(R_t = f(v_w)\) and \(\theta = f(v_w)\) relative to the mean: \(\varepsilon = f(Fr_D)\), \(\theta = f(Fr_D)\) and \(N_{tsp} = f(Fr_D)\). These indicators for models with different hull contours and additional equipment will be compared, and then conclusions about the impact of the latter on the propulsion of the planing small-class amphibious vehicles will be made.

Each model has a number from "0" to "5" in the order of the experiment. To verify the adequacy and accuracy of the generated numerical model, a comparison of the computer simulation results with the data of the full-scale experiment is made. Model "0" is the standard planing hull of the high-speed small class boat. Theoretical drawings when landing on a flat keel, configuration and weight and size characteristics of all the models are shown in Figure 3.

The drawings show coordinate systems, waterlines, and the positions of the gravity \((X_G, Z_G)\) and magnitude \((X_C, Z_C)\) centers. Graphs of reverse quality and trim depending on the Froude number for the body of the model "0" obtained during the full-scale experiment are shown in paper [6].

The types of used planing hull contours are monohedron (body with constant deadrise angle of the bottom from the transom to amidships 10–17°), low-deadrise hull (the hull with a constant deadrise angle of the bottom from the transom to amidships to 10°) and trimaran (main hull with keel and two side sponsons). A more detailed description of the types of contours of the hulls of high-speed small vessels, as well as their advantages and disadvantages is given in [2].

The effect of additional equipment on the hydrodynamic properties of planing small-class amphibious vehicles is considered, which includes the following elements: bow air tank, bow folding (or retractable) shield, stern air tanks, and transom plates.

The results of computer simulation with the data of full-scale experiment for the model "0" are compared. The combined graphs \(\varepsilon = f(Fr_D)\) and \(\theta = f(Fr_D)\) obtained during full-scale tests and numerical experiments are shown in Figure 4.
As can be seen from the graphs, in the Fr_D < 2.2 zone, the maximum divergence of values is 5 %, and the parameters obtained from field tests are more important. In the Fr_D > 2.2 zone, the maximum divergence is 6 %, and the values of the parameters determined during the numerical experiment prevail. Thus, the degree of accuracy of the generated computational model, determined by the quality of the computational grid, is 6 %.

The maximum propulsion values of the studied models are presented in Table 1.

| Parameter | Number of experiment |
|-----------|----------------------|
| ε         | 0.19 | 0.74 | 0.48 | 0.79 | 0.47 | 0.56 |
| θ, °      | 6.6  | –    | 19.4 | 22.0 | 19.0 | 19.9 |
| N_{imp}, kW/t | 28.4 | 72.2 | 47.5 | 54.2 | 27.8 | 32.7 |

* – trim is constant; ** – does not reach a maximum speed of 15 m/s

3. **Research Questions**

1. The study of hydrodynamic properties of the planing small-class amphibious vehicles with different designs of the hull and additional equipment.
2. Development of constructive measures to improve the propulsion of the planing small-class amphibious vehicles.
4. Purpose of the Study
The purpose of this study is to obtain graphs of the main propulsion indicators depending on the Froude number for the amphibian models series.

5. Methods of the Research
In the article the authors used the analytical, comparative, numerical simulation methods as well as the method of the system approach.

6. Findings
1. Model "0" has the lowest values $\varepsilon = 0.19$, $\theta = 6.6^\circ$, $N_{tsp} = 28.4$ kW/t in the range of Froude numbers $Fr_D < 5$. In addition, this case has a maximum value of static buoyancy reserve 61 % among all the studied models.

2. Model "1" has $\varepsilon$ 3.9 times greater and $N_{tsp}$ 2.5 times greater than those of the etalon model "0". Static buoyancy reserve is 56 %. This model of planing small-class amphibious vehicle has the worst hydrodynamic quality of all considered.

3. Model "2" has a 2.5 times greater $\varepsilon$, 2.9 times greater $\theta$ and 1.7 times greater $N_{tsp}$ than the standard. The use of such equipment allows reducing $\varepsilon$ by a factor of 1.6 and 1.5 times $N_{tsp}$ relatively planing small-class amphibious vehicle without him. In addition, the static buoyancy reserve increases 1.1 times and is 61 %.

4. Model "3" has a 4.2 times larger $\varepsilon$, 3.3 times larger $\theta$ and 1.9 times greater $N_{tsp}$ than the standard. In the dispersal of amphibians to this configuration, there is the effect of high trim, which requires using the high power engine or trim tabs to enter the clean mode of gliding.

5. Model "4" has a 2.5 times greater $\varepsilon$, 2.9 times greater $\theta$ than the standard. $N_{tsp}$ is comparable to the standard. Static buoyancy reserve is 48 %. This type of amphibian has the best hydrodynamic quality with respect to all studied, provides a minimum trim on the stern and requires the lowest energy intensity of the amphibian.

6. Model "5" is 2.9 times larger than $\varepsilon$, 3 times larger $\theta$ and 1.2 times greater $N_{tsp}$ than the standard. The static buoyancy reserve is equal to 53 %. This type of amphibian is inferior to the previous one in propulsion, but in terms of the set of water-moving properties, it is the best of all studied.

7. Conclusion
The propulsion study of planing small-class amphibious vehicle models with different configurations is made. As a result, it was found that with the help of additional equipment it is possible to provide less energy-consuming transition of the machine from displacement to planing mode and achieve high speeds (at least 15 m/s).

The best propulsion of all the studied models is amphibious vehicle with the contours of the "trimaran", a retractable nose shield, air tank and controlled transom plates ($\varepsilon = 0.47$, $\theta = 19^\circ$, $N_{tsp} = 27.8$ kW/t).

References
[1] Apukhtin A P 1953 Water resistance to the movement of ships (Leningrad: Mashgiz)
[2] Egorov I T 1971 Hydrodynamics of high-speed vessels (Leningrad: Sudostroenie)
[3] Basin A M 1969 Propulsion and handling of ships (Moscow: Transport)
[4] Filatov V V 2017 Hydrodynamic study of perspective high-speed small-class amphibious vehicle Bull. of civil engineers 2(61) 219
[5] Pechenyk A V 2015 Optimization of ship hull form to reduce resistance to movement Digital Marine Technol. 2 10–20
[6] Clement E P and Blaunt D L 1963 Resistance tests of a systematic series of planing hull forms Society of Naval Architects and Marine Engineers 491