9. Яблочников Е.И. Автоматизация технологической подготовки производства в приборостроении / Учебное пособие. СПб: СПбГИТМО (ТУ), 2002. 92 с.

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СТАБИЛИЗАЦИЯ ПРОДОЛЬНОГОДВИЖЕНИЯ ПОДВОДНОГО АППАРАТА

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STABILIZATION OF LONGITUDINAL MOTION OF UNDERWATER VEHICLE

Annotation. The mode of longitudinal motion of attached underwater vehicles under the action of propulsors is considered. The behavior of the devices in the aqueous environment and methods of stabilizing their movement are analyzed. Since among the machines it is possible to find both well-streamlined bodies and low-mobility platforms carrying equipment open to water, approaches to solving this problem differ. Often, the devices are required to have increased maneuverability, and the walking is sidelined. From here approaches to selection of power armament and propulsion-steering complex are formed. When calculating statics and dynamics, there are features that distinguish underwater vehicles from conventional floating objects. For them, in most cases, high stability cannot be achieved. It is necessary to provide either excessive volumes inside the pressure hull, not used for equipment accommodation, or additional buoyancy units made of light material, located outside the pressure hull of the apparatus. The ability to lower the centre of gravity by moving the equipment is also limited. Therefore, there is a problem in providing the necessary stability both in static and dynamic, although for an underwater vehicle the concept of rollover differs significantly from surface vessels. The method of selection in the first approximation of the minimum required metacentrical altitude for binding systems is proposed. Ways of stability regulation and its rationing are proposed.

Keywords: stability, underwater vehicle, motion stabilization, metacentric height, stability regulation.

Introduction

When designing attached underwater vehicles, the question arises about the use of special devices or structural measures stabilizing their movement in different planes. The main movements of the apparatus are horizontal and vertical displacement. Disturbances in movement have different causes. This can be poor hydrodynamic balancing, lateral flow, housing asymmetry, etc. The nature of the flow related to the difference in speed and shape of the body also differs. In fact, among the machines there can be found well-streamlined bodies designed for movement at high relative speeds, and low-mobility platforms carrying equipment, open to the action of water and designed to perform works in the local space.

Numerous researchers have studied the stability of underwater vehicles Professor. A. Basin, in a fundamental work on stability and controllability of ships [1] as early as 1949, gave generalized formulas for calculating the steering devices of surface vessels, which can be used to assess automatic stability of traffic, in relation to surface objects. Pantov E.., and a group of researchers in 1973 formulated the main mathematical provisions of the theory of movement of autonomous underwater vehicles [2], but their work is rather staged and gives a wide field for researchers. Greiner L. in 1978 in his work on hydrodynamics and power engineering of underwater vehicles [3] offers several private solutions for choosing the shape and stabilizing devices of autonomous underwater vehicles. However, the author of the monograph considers mainly well-streamlined bodies without touching on the issues of poorly streamlined structures. On the contrary, S.Devnin 's work on aerodynamics of bad-flowing structures of 1983 [4], Y. Wojtkunsky 's directories of 1985 [5] and V. Droblenkov of 1984 [6], gives numerous data on resistance coefficients and joined masses for bodies of various shapes, which can be applied in calculations. Academician M. Ageev in a monograph on automated underwater vehicles [7] in 1981 gave practical recommendations for the design of autonomous PA, but the issues of control and stability of the movement remained unsolved. Professors B.Slyzhevsky[8] gives a number of original theoretical justifications for determining static and dynamic stability of AUV, but from a practical point of view the technique offered by him is quite complex and does not allow for comparative analysis of the results. The author of this work also solved a number of private tasks on stability of AUV movement [9].

The purpose of this article is to develop a methodology for determining the metacentric height for different types of underwater vehicles at the initial stages of design. Design methods are proposed, which allow to simplify procedure of selection of metacentric height determining character of apparatus motion in interested modes.

It is important to note that actually we consider group of underwater objects which form - badly streamline bodies with rather low speeds of movement which have Re ≤ 0.5x106 and ratios of L/B B/H about 1.0; They have no waterline in underwater position, and stability is determined only by mutual position of center of gravity and center of boyancy. Therefore, the static stability diagram has positive stability arm values and a sinusoidal view provided that the center of gravity is below the center of boyancy.

$$M_B = G\ h\ \sin\Theta = G(\rho + Zc - Zg)$$

The G-displacement values, h-metacentric height, p, Zc, Zg (metacentric radius, center-of-magnitude and center-of-gravity applications) at the incline maintain constant values, regardless of the angle of incline. Positive stability at inclination from 0 to 180 degrees is provided by condition Zc > Zg; at which the vehicle is always stable. The greatest restoring moment arises at angle of heel of Θ = 90 degrees. Despite this, however, the center of boyancy of the greatest allowed tilts is limited by operational requirements.

The underwater vehicle family includes many varieties. They are of architectural and structural type, including hull shape, structural elements, motion systems, control systems and component equipment. The NPA motion equations in this case will be fair if the yaw and trim coals are small and practically do not exceed 10 degrees. In general, the coordinates of the center of gravity Zg, the center of magnitude Zc, and the center of lateral resistance Xgh do not coincide. Vertical or transverse stability of the vehicle shall be ensured provided

$$Zc - Zg > 0; \qquad (1)$$

This is a necessary but not sufficient condition for sustained longitudinal movement. In addition, we impose a restriction: the center of lateral resistance Xhg should be more aft than Xg and Xc. In fact, we need to find out at what values

$$Zc - Zg = h; \text{ and } Xs - Xhg > 0;$$

Stable motion in preset direction. When designing underwater vehicles, typical stability calculations often have to be supplemented by experimental data. As such an experiment, design studies and in-kind tests of the general arrangement and weight load of five underwater vehicles of poor flow shape with displacement from 32 to 400 kg were carried out. The general location of each of the projects was developed and the weight load composition was determined. Each of the variants was refined and had positive stability, which could be changed by means of cargoes. Basin and in-kind tests were carried out to determine the metacentric height of each of the projects, which at a given speed provided its horizontal and vertical movement with a roll of not more than 3-5 degrees. Determination of the position of the center of gravity and arm of stability was accompanied by graphical studies and calculations according to the admiralty formula. Data from technical specifications and other documents for equipment were used in calculating the weight of the machines. In-kind experiments were processed as tables and graphs.

For convenience of comparative analysis of the level of required stability, the LBH module, which is the product of the main dimensions of the object, was executed. General view and diagrams of the layout of «Scarabey», «Diaf 300 "and" Posseidon-M " projects are shown in figures 1, 2, 3. Different speed modes of movement are considered to show dynamics of required change h.

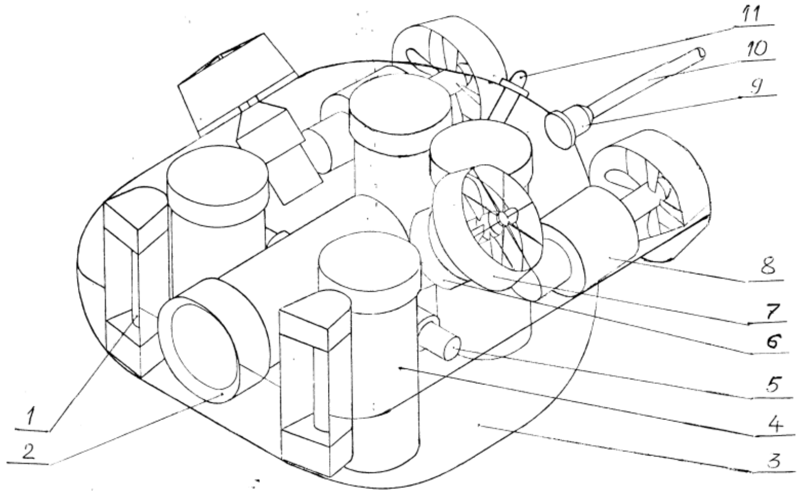


Fig. 1- General view and layout of ROV "Scarabey": working depth, m - 200; overall dimensions of the ROV, m - 0.78 x0.60x0.55; ROV speed, m/s: cruise - 1.6; Vertical - 1.2; h.

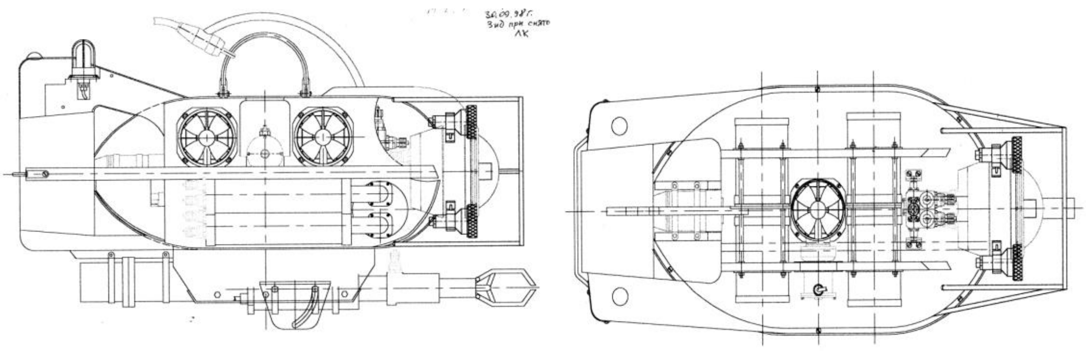


Fig. 2- General view and layout of multi-purpose ROV "Diaf 300" operating depth, m - 300; overall dimensions of the ROV, m - 1.20x0.66x0.68; ROV speed, m/s: cruise - 2.6; Vertical - 1.2; ROV weight, kg - 83.

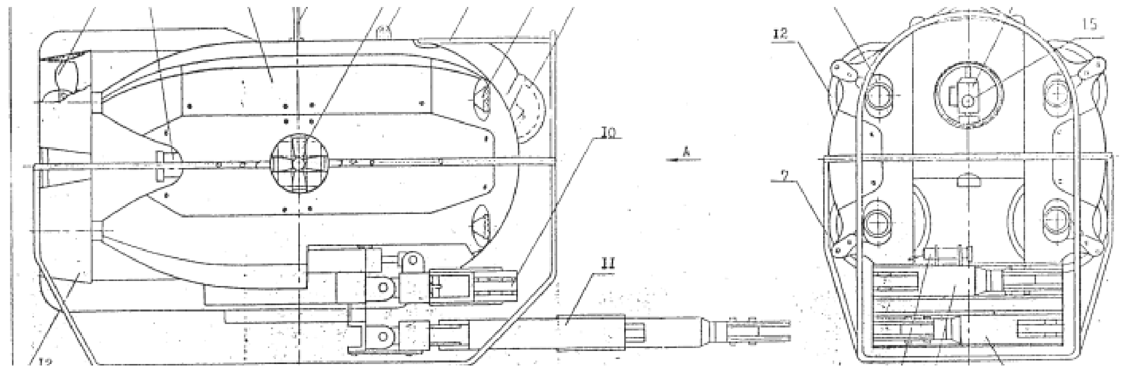


Fig. 3- General view of ROV "Possedon -M" layout and characteristics: working depth, m - 600; overall dimensions of the ROV, m - 1.55x1.10x1.0; ROV speed, m/s: cruise - 2.2; Vertical - 1.50; ROV weight, kg - 240.

The processing of the results of the in-kind tests of the above-mentioned series of projects carried out during the period of 1995- 2008 made it possible to summarize the results and make the assumption that in order to obtain satisfactory design results the stability of the devices must meet the minimum requirements, with a positive value h of the metacentric height. The main dimensions and cubic module of the five projects are given in table 1. Measurement results h presented in Figure 6 make it possible to predict with certain assumptions the minimum required value of metacentric altitude.

Table 1

Ganeral Dimensions and cubic project module

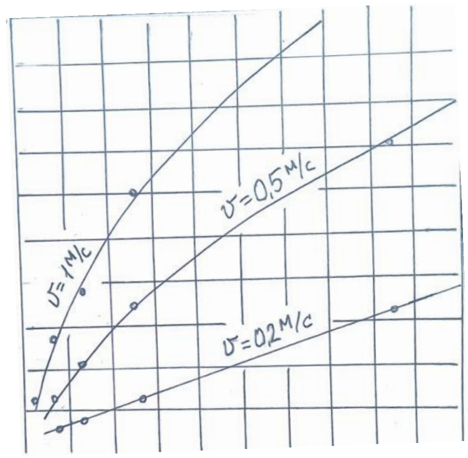
LxBxH,m	0,68x0,58x0,40	0,78x0,60x0,55	1,2x0,66x0,68	1,55x1,10x1,0	1,70x1,20x1,00
LBH,m^3	0,157	0,258	0,539	1,705	2.040

Graphs of change of metacentric altitude **h** corresponding to different speeds are shown in Fig. 4. These h values guarantee minimum sufficient stability of the apparatus during horizontal and vertical movements. For early design calculations, you can use the graph approximation (Fig. 4).

$$h = 0{,}098(v)^{0,67}\ (LBH)^{0,5}; \qquad (2)$$

where v - design speed of the vehicle, m/s

With regard to static and dynamics calculations, there are features that distinguish the apparatus from conventional floating objects. Possibilities of decrease in the center of gravity of an object are limited to motions of the equipment. In the design it is necessary to provide either excessive volumes inside the pressure hull, not used for equipment accommodation, or additional buoyancy units made of light material, located outside the pressure hull of the apparatus. In this regard, there is a problem with compensation for the action of external forces both in static and dynamic, although for an underwater vehicle the concept of rollover takes on a different content, because roll can reach 1800. If it is possible to provide an arm of vertical stability of about 7-8% of the height of the apparatus structure, this can be considered an acceptable result.



h

0 0,4 0,8 1,2 1,6 2,0 LBH

Fig. 4. Dependence of metacentrical height h on dimensions and speed of ROV movement while providing the condition of its stable movement movement while providing the condition of its stable movement

In general, the condition of steady movement of ROV is defined by the expression

$\mathbf{M_w > M_o}$;

Where M_w and M_o recover and rollover moments acting on the moving object. With this condition in mind, consider at what ratios of geometric dimensions and mass distribution along the length and height of the apparatus the ratio (5) is fulfilled.

In addition to the problem of low stability, underwater technological vehicles are characterized by contact interaction with other objects. It is necessary to suppress the reaction from the object of work and to maintain the spatial position of the apparatus. This will contribute to the effective implementation of the task. Contacts can be unpredictable, there may be bursts of effort in magnitude and time of action. It is necessary to react to them, and in any control system there are such negative effects as delay of signals, inertia of actuators, inaccuracies of mathematical models of processes and software. In this connection, it is advantageous, in addition to means for controlling the position of the apparatus, to provide fixing devices on the apparatus using various physical principles - mechanical grips, pneumatic suckers, electromagnets, etc. It is obvious that issues of stability of underwater vehicles, as well as issues of buoyancy, cannot be solved in isolation. In close association with them will be tasks of dynamics, and parameters of component devices and systems.

The issue of evaluation and assignment of dynamic stability contains many unresolved theoretical issues. One is damping accounting. For surface vessels, damping is generally not taken into account. This is justified because of the small damping moment compared to the recovery moment at transverse inclination. It is also known that real dynamic loads for surface vessels very rarely lead to rollover. Their maximum restoring moment occurs at roll 55-60^0, and for underwater objects dynamic equilibrium occurs at roll about 90^0degrees and is caused by smaller external trimming moment. If to introduce restriction on dynamic angle of heel, for example, to accept $\psi < 75^0$, then the ratio between the maximum permissible external moments even more favors accounting of damping. Taking into account the assessment on two criteria - by moment and by angle, it can be argued that the real dynamic stability of the underwater vehicle, as quality, is significantly higher than that determined under the traditional approach.

Under action of suddenly applied trimming moment the device acquires increasing angular speed and angular acceleration. In the first step of tilting, the velocity increases from zero to maximum, and then in the second step falls to zero when dynamic equilibrium occurs. The zero velocity of the second stage corresponds to the highest dynamic roll. At the same time large projecting parts play a positive role, increasing the period of inclination. The motion of the vehicle is described by a linear differential equation of the second order.

$$(1+ k_{55})\ \ddot{\psi} + \psi k + GH\psi = M$$

The resistance at angular movements in the longitudinal plane is significant and similar external effects should be taken into account by separate verification calculations.

The situation is slightly different with the second group, with a large extension of the hull. In most cases the circular form of the case of the device at relative lengthening of L/D ≥ 5 possesses small metacentric height and dependence of hydrodynamic characteristics on kinematic parameters of the movement. Many autonomous vehicles (AUV) have both fixed and movable horizontal and vertical rudders (ailerons). At turning of planes by angles δ_L and δ_R, trimming moment of control is determined by their average value, and rolling moment $-\delta_Г = 0{,}5(\delta_л + \delta_п)$ by difference $\Delta\delta_Г = \delta_л - \delta_п$. Another structural feature of the AUV is that in a single-shaft propulsion system, the propulsor creates a tipping moment causing the apparatus to roll. And only with two coaxial screws with opposite rotation can this be avoided. The two-shaft arrangement is devoid of this disadvantage. Thrust is oriented along O_x axis. Accompanying trimming and heeling moments that could play the role of additional perturbations are excluded

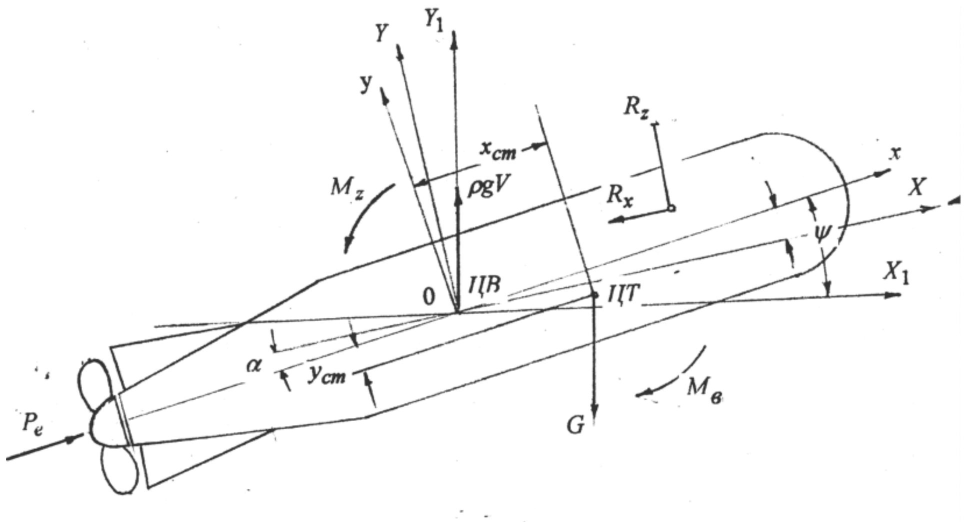


Figure 7. - Action of external forces on the maneuvering autonomous underwater vehicle

The external forces and moments represented by a system of 6 equations must be supplemented by general relationship equations. This model is used to analyze the deep maneuvering of the vehicle, roll and trim. Small maneuvering and stabilization modes can be investigated by simplified linearized equations. When drawing up equations of AUV dynamics, bear in mind that its shape of frames may not correspond to circular shape. In order to increase stability of the apparatus, the skids are designed in the form of a vertically elongated ellipsoid with a developed stern in the form of stabilizers, vertical rudders and ailerons (Fig. 7). Therefore, nondiagonal elements must also be considered in the matrix of joined masses and moments of inertia. In the case of symmetry of the apparatus with respect to the longitudinal axis, in addition to diagonal coefficients of the connected masses λ_{11}, λ_{22} λ_{33}, λ_{44}, λ_{55}, λ_{66}, the significant values are $\lambda_{26} = \lambda_{62}$ and $\lambda_{35} = \lambda_{53}$. The equations of the dynamics of the spatial motion of the AUV in general form are converted into a system of 6 diferinical equations [10]. During movement there are small fluctuations of state variables (angles of attack and drift, yaw, roll and trim) and control actions (angles of vertical and horizontal rudders movement). The assumption of small Euler angle values allows for simplified coupling equations. With good hydrodynamic balancing of the apparatus, when the point of application of displacement force is reached with the center of mass, the equations of lateral and longitudinal movement of the AUV are independent. The specificity of underwater vehicles is evident in the absence of positional moments in the equations of on-board and keel rolling. There are also no positional forces in the vertical displacement equation. This means that the apparatus has very low static stability and its stable movement, as well as maneuvering, can be provided by vertical and horizontal rudders [9, 10].

The use of mathematical modeling in the initial stages of design is time consuming and not always justified. In most cases, it is proposed to use a simplified methodology for assessing the stability of the AUV and constructive measures to ensure sustainable movement in a given direction. The second part of the experimental work consisted of towing non-navigational torpedo-shaped models with circular frames, the relative elongation changed from 4.6 to 8.8. The area of feed stabilizers also changed. The metacentric height of the towed objects was kept constant at 10% of the hull diameter. Like previous reasoning, let us turn to condition (3).

The tipping and restoring moments can be represented as (5), (6). Where vxis the translational velocity; S_x is the area of the projection of the apparatus onto the X_Y plane; S_{st} is the area of stabilizers; X_h and

X_{st} coordinate points of lateral resistance of the housing and stabilizers.

$$M_{опр} = 0{,}5\rho(v_x)^2 Sx\, C_x(x_c - x_{gh})\sin\psi \qquad (5)$$

$$M_{вос} = 0{,}5\rho(v_x)^2 S_{ст}\, C_y(x_c - x_{ст})\sin\psi \qquad (6)$$

The lift factor of the shaped stabilizer varies at different angles of attack of the incoming flow α. In the range of 3-10 degrees, formula (7) can be recommended for the evaluation of Bc [11, 12]

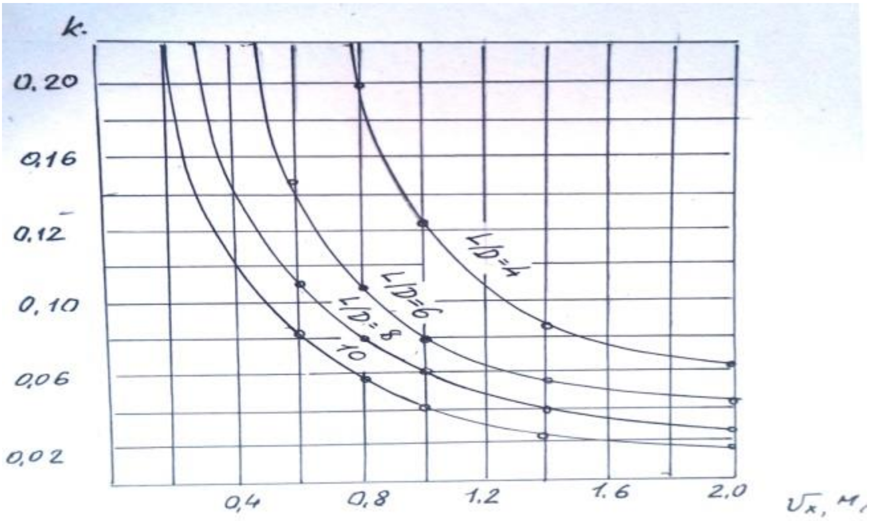


Рисунок 8. Зависимости коэффициента k_x от скорости аппарата и относительного удлинения L/D.

$$C_y = (1{,}1Re10^{-7} + \frac{6\alpha}{57{,}3} - 0{,}15);$$

As a result of working with formulas (5) and (6), you can plot relationship dependencies $S_{st}/(Sh) = k_x$ as a function of the speed and elongation of the vehicle. These graphs can be approximated by formula (8).

$$k_x = (0{,}015\ 0{,}36D/VxL\ ) \qquad (8)$$

The k_x coefficient with a relative error of 7-10% allows to assign the area of stabilizing devices for the AUV in the range of speeds of 1-4 knots.

Conclusions

Analysis of experimental data of design variants of models and natural objects indicates that:

1. The greatest influence on the selection of the area of stabilizers is the speed of operation of the apparatus, to a lesser extent the external shape and the ratio of the main dimensions L/H or L/D.

2. Constraints (2) and (8) can be used to estimate the stability of the initial design stage, which, with an accuracy of 7-10%, allow to determine the required value of metacentric height or area of stabilizers at the early stages of the design.

3. As the size of the vehicle increases, the possibility of varying the position of the centres of gravity and magnitude expands.

4. For an AUV with a well-streamlined body shape, the area of stabilizing devices depends mainly on speed and weakly on the relative distance of the body asymthotically approaching kx to 2%.

List of References

1. Basin A.M., Stability Theory on Course and Turnability of Ships. L.: Gosteh theories, 1949 g.226 p. 110-114s.

2. Pantov E., Mahin N., Sherememetov B., Foundations of the Theory of Movement of Underwater Vehicles. L.: Shipbuilding, 1973. -211. page 45-54.

3. L. Greiner, Hydrodynamics and Energy of Underwater Vehicles, L.: Shipbuilding, 1978, 256 p. 26-38.6.

4. Devnin S.I., Aerodynamics of Bad Flowing Structures, Reference Manual. L.: Shipbuilding, 1983. 126 page 76 - 83.

5. Woitkunsky Y.I. Handbook on ship theory (in three volumes) L.: 1985 PDF/J Wu, Rus.768 pp. 389-394.

6. Droblenkov V.F., Yermolayev A.I., Moor N.P. et al. Ship Theory Handbook. Moscow, Voyzdat, 1984 - 589 pp. 267-271.

7. Ageev M.D., Kasatkin B.A., Kiselev L.V. et al. Automatic underwater vehicles. - Leningrad: Shipbuilding, 1981, 234str, il.

8. Slizhevsky. N.B., Walking and controllability of underwater equipment. Tutorial. -Nikolayev: UGMTU 1998. -148c. p. il.

9. Vashedchenko A.N., Pyshnev S.N., Rodichev A.P. Some calculations in the design of underwater vehicles. Tutorial - Nikolayev, UGMTU, 1997, 66 c.23-38.