Management of towed geophysical systems when exploring a shelf

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Abstract. Much attention is paid to the equipping of special geological (geophysical) vessels with multi-purpose towed complexes capable of solving a wide range of research tasks in a ship traffic lane. Organization of such works in a traffic lane of a shelf research carrier vessel, as leveling of the bottom surface, phototelevision recording of local objects, taking soil and water samples, determining the radioactivity of water and soil, requires a systematic approach to the use of a geophysical outboard complex. The article considers ensuring the required quality of movement of a geophysical outboard complex, according to the required dynamics parameters at different towing speeds and safe operation of a geophysical outboard complex.

Keywords: underwater vehicle, geophysical vessel, geophysical outboard complex, marine equipment, towing speed, trajectory of the underwater vehicle, lateral displacement, sinking force, diverting force

1. Introduction
The development of marine technology for oil exploration and production reflects technological and intellectual capabilities of the country.

The article is devoted to the development of control complexes of geophysical equipment for the study of the sea shelf. Research at sea are characterized by the use of moving instruments. This movement can be caused by research tactics – towing or probing, or it is associated with current or drift. In addition, an important advantage of towed devices (apparatuses) is the possibility of operational inspection of vast water areas with the simultaneous use of a whole complex of measuring devices. The movement speed of towed vehicles relative to the environment can range from units to hundreds of centimeters per second. A complex structure of the distribution of the hydrological environment parameters and the morphology of the bottom relief in space may affect errors and distortions of the obtained images of the bottom surface and underwater objects may occur when the vehicles move.

In this regard, an urgent problem is the development and study of the main criteria for choosing the optimal towing speed of underwater vehicles designed to survey the bottom surface and the bottom boundary layer [1], based on the requirements imposed by the operating conditions of the entire hardware complex and the technical capabilities of the systems included in it.

The purpose of the current study is the synthesis of a control system for a geophysical outboard complex (GOK). Improving the efficiency, including the productivity and use of SLC for the study of the sea shelf.
2. Materials and Methods

The ship control system presents an adaptive control system. Adaptive control is aimed to determine the input parameters of motion. In our case, these are readings of latitude and longitude coordinates, for the center of mass of the ship rotation. Taking into account the use of outboard equipment as part of the complex, separately in the technological scheme, the input parameters for the complex present also latitude and longitude readings for the outboard equipment complex.

The analysis of the literature shows that the following types of automatic control of geophysical systems can be distinguished:

- stabilization of motion parameters (stabilization of course, speed, depth, etc.) [7];
- adaptive control is the control with automatic adjustment of regulators or control systems when changing the parameters or the characteristics of the external environment [8];
- program control is automatic movement along a program-defined underwater trajectory;
- intelligent control based on the construction of intelligent information systems (logical, logical-probabilistic and fuzzy knowledge bases) for modeling unknown obstacles based on local sensory information from informational system or virtual reality models, for modeling short trajectories of the geophysical system in an environment with known or unknown obstacles, etc. [9].

The use of PD and PID controllers is characterized by significant disadvantages, such as the complexity of their configuration.

In our work, we will consider adaptive control and modern directions for the synthesis of control of the underwater towed apparatus of a geophysical system in the shelf study.

Figure 1 shows a method for obtaining an error signal in a system with five inputs by introducing a useful response. To generate an error signal $\varepsilon_k$, the output signal $y_k$ is simply subtracted from the useful response $d_k$ and it follows that the error signal

$$
\varepsilon_k = d_k - y_k
$$

where $d_k$ is the useful or reference positioning signal, $y_k = X_k^T W_k$ is the output signal for determining the current coordinates, while $X_k^T$ indicates the samples of the current coordinates, $W_k$ is the matrix of the vector of the input coordinates.

Or

$$
\varepsilon_k = d_k - X_k^T W = d_k - W^T X_k,
$$

Taking into account the stationary nature of the hydrodynamic problem of ship movement:

$$
R = E[X_k X_k^T] = E\begin{bmatrix}
x_{0k}^2 & x_{0k} x_{1k} & x_{0k} x_{2k} & \cdots & x_{0k} x_{Lk} \\
x_{1k} x_{0k} & x_{1k}^2 & x_{1k} x_{2k} & \cdots & x_{1k} x_{Lk} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
x_{Lk} x_{0k} & x_{Lk} x_{1k} & x_{Lk} x_{2k} & \cdots & x_{Lk}^2
\end{bmatrix},
$$

where $R$ is the square matrix of the mean-square deviation (MSD), coordinates.
Figure 1. Useful response and error signals in a neural network with five inputs, \( d_k \) is a useful response signal; \( y_k \) is an output signal; \( \varepsilon_k \) is an error signal; \( W_{1k}, W_{2k}, W_{3k}, W_{4k}, W_{5k} \) are calibration coefficients[1].

Instantaneous quadratic value of the error signal:
\[
\varepsilon^2_k = d^2_k + W^T X_k X_k^T W - 2d_k X_k^T W,
\]
then the error signal MSD:
\[
\xi = E[\varepsilon^2_k] = E[d^2_k] + W^T RW - 2P^T W.
\]
where \( P \) is the matrix of the intercorrelation function of the input samples and the reference signal.

A two-dimensional MSD function can be represented by a quadratic surface, a graph of a two-dimensional quadratic working function. The cross-sections of the surface determine a set of coefficients of the system that ensure the approximation of a random function to a set of criteria for the control quality, the accuracy of binding to the current coordinates [2].

The most optimal methods for adapting the working function of the coordinate transformation and the subsequent calculation of the eigenvector of the system include the methods of steepest descent, the Newton method, etc. Furthermore, good results are obtained by the method of training curves.

It is obvious that the search for the gradient of the working function (5) is solved optimal data filtering in the adaptive recursive filter of the system [1].

Adaptive automatic motion control systems of the GOK are effective, however, they require complex mathematical models of the dynamics of the spatial motion in conditions of external disturbances, which significantly complicates the technical implementation of such systems.

3. Results and discussion
Studies in the conditions of waves and wind disturbances using outboard equipment should entirely describe the dynamics of the vessel and the active control means of the height of the outboard equipment from the bottom surface.

The system of the geophysical complex includes an altimeter installed on a ZBC and a sonar. While additional measures to achieve stabilization by inertial stabilization systems require additional energy costs, and therefore an increase in the mass of cables, which already requires changing the entire complex as a whole.
In the Federal State Unitary Enterprise "Krylov State Scientific Center", St. Petersburg, the methods of numerical integration are calculated:
- length of the cable rope, 100 m;
- deepening of the running end relative to the root, 40 m;
- diameter of the cable rope, 15 mm;
- weight of the cable in the water, 1.2 N/m.

Figure 2 shows a block diagram of the control system, which includes a control joystick that sets the towing height of the device, a computer that generates control signals, a communication system with an RS-232 interface, an on-board microcontroller, vertical movement drives (microcontrollers, PWM inverters, electric motors, screws), a control object (the towed device). A roll, a trim and yaw sensors are included in a positive feedback circuit.

In order to develop a control system and dynamic stabilization, it is necessary to investigate algorithms for controlling the engines of movement in the vertical direction in proportion to the joystick signals entered in the height selection mode.

In the mode of automatic maintenance of the device movement of the at a given distance from the bottom surface, it is necessary to ensure the selected height of the movement of the device, as well as to ensure the quality of stabilization according to the trim parameters.

The control parameters were obtained from a full-scale experiment conducted at the Federal State Unitary Enterprise "Krylov State Scientific Center" [5]:
- towing speed - from 0, 5 -3 m/s;
- lateral displacement of the ZBC is from 20.0 - 40.0 m;
- demolition of the ZBC downstream from 79.6 – 91.0 m;
- The sinking force is 0.0-647 N;
- The diverting force is 0.0-717 N.

At low towing speeds of around 2 knots, it is possible to use active controls to give the carrier maneuvering properties. At high speeds, the use of active elements is not energetically justified, but it should be expected that passive elements - steering planes - can work effectively.

The balance of the ratio of active and passive controls to achieve the required efficiency when maneuvering in a large range of towing speeds requires additional detailed studies.

In addition, it is necessary to carry out such calculations in a dynamic formulation, i.e. to assess how sensitively the ZBC reacts to the effects by the active elements.

Calculations of the dynamics of the ZBC behavior were carried out for a range of towing speeds from 1 to 3 knots, a cable length of 75 m (with a diameter of 15 mm and a weight of 1.2 N/m in water) with a sinking of the running end relative to the root, equal to 20 m, and a mass of the ZBC of 825 kg.
An example of the results of the test calculations demonstrating the parameters of lag motion (displacement, speed and acceleration) as a function of time for a towing speed of 2 knots and a diverting force of 126 N is presented in Figure 3. It can be seen that the lag movement is a rapidly decaying oscillatory process around the stationary position at a distance of 20 m from the trajectory of the GOK. The exit to a given tack in a corridor with a width of 1 m can be completed in 1.5-2.0 minutes. In practice, the fluctuations can be leveled by applying the appropriate law of control of the diverting force.

![Figure 3. Dependence of the parameters of the lag motion of the vehicle in time](image)

The results of the main calculations in the form of the trajectory of the ZBC movement are presented in Figures 4-6. It is obvious that with an increase in the towing speed and a decrease in the diverting force, the maneuverability of the ZBC decreases. At the lowest speed (1 km) and at the maximum diverting force (200 N), the value of the step displacement of the vehicle relative to the short circuit can reach 60 m. It will take about 3 minutes to rebuild. Half the distance can be reached in 1 minute. And at a speed of 2 knots, such a displacement – 28 m is the maximum achievable, it will take about 1.5 minutes to maneuver.

![Figure 4. The trajectory of the vehicle at a towing speed 0.5 m/s](image)
Taking into account the fact that the initial phase of the vehicle trajectory is almost straight, an interesting indicator of maneuverability in this situation may be the angle $g$ of the vehicle deviation trajectory from the towing direction, shown in Figure 7. This indicator enables to judge the ratio of marching and lag movements. The dependence of this angle on the towing speed and the pulling force is shown in Figure 7. In the considered range of initial data, the maximum angle can be 40-45°.
Figure 8 shows the initial phase of the vehicle movement for the case presented in Figure 7 (the same dependencies, but on a different scale). The movement becomes stable, close to straight, starting from the 3rd second. By this time, the PA passes about 40 cm. In the first second, it shifts by only 5 cm, i.e. there is a non-linearity associated with the inertia of the device.

General conclusions on the maneuverable properties of the PA in the horizontal plane are:

- the technical parameters of the complex provide the possibility of installing vertical and lag propellers on the PA, providing at towing speeds from 1 to 3 knots to make the transition to passing tacks that are 60 m away from the trajectory of the GOK, respectively; the depth of the ZBC relative to the GOK can be 20-40 m;
  - the duration of transients at the maximum lead can reach 3 minutes;
  - the angle between the initial section of the trajectory of the PA, passing on a passing tack, and the direction of towing reaches 40-45°.
- low functional efficiency of the maneuvering procedure in terms of tracking extended objects.
- unjustifiably high power consumption with a significant deviation from the trajectory of towing the ZBC. It should be expected that the value of the generated stops to give the carrier high dynamism increases, which leads to an increase in energy consumption.

Based on the results of calculations for towing speeds of one, two and three speed nodes, we form a rule base of the fuzzy inference system and determine the input and output linguistic variables.

We set 3 input variables: "towing speed", "lateral displacement of the ZBC", "demolition of the GOK downstream", and two output variables named "sinking force", "diverting force" [4].

We develop a fuzzy model (Towed vehicle) using the Fuzzy Logic application of the MATLAB system.

The cross-sections of the uncertainty body within the boundaries of the specified adjustment values of the regulators determine the influence of the associated values of the regulators on the process of self-leveling of the control object (Figure 9).
Figure 9. Visualization of the fuzzy output surface for the fuzzy output system of the tuning parameters of the GOK control system

4. Conclusion
The resulting body of fuzzy output distributions enables to establish the dependence of the values of the output quantities on the values of the input variables in the fuzzy output system.

The simulation results provide implementing the technology of high-quality control of towed geophysical systems during the study of the shelf.

At speeds up to 2 knots, the required forces contain practically realizable values. For the towing option, the total force of the necessary stops at a speed of 3 knots presents already 1364 N, which requires approximately 13.5 kW of electricity supplied to the propellers.

The solution of these problems enables to obtain values and calculated ratios for the maximum permissible speeds of movement when studying the bottom surface of the bottom area of water territories. Thus, the article solves the main aspects of increasing efficiency when maneuvering in a large range of speeds of underwater towed vehicles based on the analysis of the main criteria for choosing the optimal towing speed of GOK intended for examining the bottom surface and the bottom boundary layer.

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