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THE USE OF EXCESSIVE ACTUATORS STRUCTURES IN AUTOMATIC VESSEL MOVEMENT CONTROL SYSTEMS

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ВИКОРИСТАННЯ НАДЛИШКОВИХ СТРУКТУР ВИКОНАВЧИХ ПРИСТРОЇВ В АВТОМАТИЧНИХ СИСТЕМАХ КЕРУВАННЯ РУХОМ СУДНА

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Херсонська державна морська академія

ИСПОЛЬЗОВАНИЕ ИЗБЫТОЧНЫХ СТРУКТУР ИСПОЛНИТЕЛЬНЫХ УСТРОЙСТВ В АВТОМАТИЧЕСКИХ СИСТЕМАХ УПРАВЛЕНИЯ ДВИЖЕНИЕМ СУДНА

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Currently a large number of vessels such as Platform supply vessel (PSV) / Offshore Support Vessel (OSV), Diving Support (DSV's) and ROV Support Vessels, Drill Ships, Cable Lay and Repair Vessels, Pipe Laying Ships, Dredgers, Crane Barge or Crane Vessel, Rock Dumping Vessels, Passenger Vessels, Specialist – Semi-submersible Heavy-Lift Vessels, Mobile Offshore Drilling Units / Ships (MODUs), Shuttle Tanker, Naval Vessels and Operations [1], operate under risk conditions, therefore there are increased requirements for reliability, accuracy and maneuverability. To meet these requirements, the control systems such vessels, which

is called a dynamic positioning system (DP-system), are equipped with high-precision measuring devices that allow determining with high accuracy the absolute position of the vessel (DGPS systems), or the position relative to another object (Reference systems), redundant control structures that ensure reliability in control, on-board computer complex and software for the automation of control processes [2, 3]. These vessels have the greatest degree of control processes automation in order to minimize the influence of the human factor. Human factor is the weakest link in the vessel control system [4–6]. The issues of improving control efficiency through the use of automated systems have also been considered by the authors earlier. So, in article [7, 8] there were considered the issues of increasing reliability due to automatic detection and parrying of failures, in articles [9, 10] there were considered the issues of automatic divergence with many targets, including maneuvering ones and in article [11] there were considered the issues of increasing the control accuracy due to the use of the meter mathematical model in on-board controller. Control redundancy is typically used to improve reliability. At the same time, redundancy in control can also be used to increase the efficiency of the control system [12, 13]. To ensure three-dimensional controllability simultaneously in the channels of longitudinal, lateral and rotational movements, the minimum required number of independent controls should be $U = 3$. At the same time, on many transport vessels the number of independent controls is $U = 2$ (the angle of the telegraph and the angle of the stern rudder). On such vessels, one stern rudder is used for sequential development of lateral and angular deviations (first, lateral deviation is worked out by changing the course, then the course itself is worked out). In the presence of external influences, such vessels move along a trajectory with a drift angle, which leads to additional fuel consumption. The use of schemes with sufficient $U = 3$ control already makes it possible to increase the reliability (due to the use of an additional rudder) and the quality of control (due to the possibility of keeping the vessel on the route with a zero drift angle, reducing the hydrodynamic drag, saving fuel, reducing emissions, preservation of the environment).

Fig. 1 shows a control scheme of the considered excessive structure.

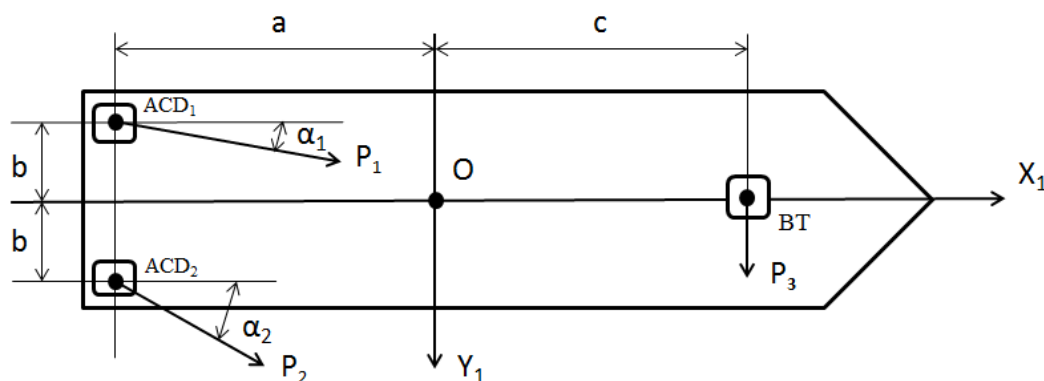


Fig. 1 – Control scheme of the considered excessive structure

The control structure consists of two stern azimuth control devices ACD_1 , ACD_2 and a bow thruster BT .

It is required to find such control parameters $P_1, \alpha_1, P_2, \alpha_2, P_3$, that would ensure the optimization of the control quality function (1) in the presence of control constraints (2) and (3).

$$Q(P_1, P_2, P_3) \Rightarrow opt, \quad (1)$$

$$\mathbf{U} = \mathbf{f}_u(P_1, \alpha_1, P_2, \alpha_2, P_3), \quad (2)$$

$$|P_1| \leq P_1^{\max}, |P_2| \leq P_2^{\max}, |P_3| \leq P_3^{\max}, |\alpha_1| \leq \pi, |\alpha_2| \leq \pi, \quad (3)$$

where $Q(\bullet)$ is the quality control function,

$\mathbf{U} = (P_x, P_y, M_z)$ is the vector of required control forces and moments in control channels,

$\mathbf{f}_u(\bullet)$ is the mathematical model of the control structure,

P_1, P_2 is the thrust force of the screw of the first and second ACD, respectively,

α_1, α_2 is the rotation angle of the first and second ACD respectively,

P_3 is the bow thruster force.

The mathematical model $\mathbf{f}_u(\bullet)$ of the control structure (2), in projections on the axis of the related coordinate system, has the form

$$P_x = P_1 \cos \alpha_1 + P_2 \cos \alpha_2, \quad (4)$$

$$P_y = P_1 \sin \alpha_1 + P_2 \sin \alpha_2 + P_3, \quad (5)$$

$$M_z = P_1 b \cos \alpha_1 - P_2 b \cos \alpha_2 - P_1 a \sin \alpha_1 - P_2 a \sin \alpha_2 + P_3 c. \quad (6)$$

As can be seen from equations (4)–(6), for the implementation of control actions P_x, P_y, M_z in the channels of longitudinal, lateral and rotational motions, respectively, there are five control parameters $P_1, \alpha_1, P_2, \alpha_2, P_3$, that is, the control redundancy for the considered control structure is $5 - 3 = 2$. Redundancy in control means the availability of free control parameters that can be used to optimize control processes. Below we will consider optimal controls of the considered redundant structure for the following control quality functions:

$$Q_1(P_1, P_2, P_3) = P_1^2 + P_2^2 + P_3^2 \rightarrow \min. \quad (7)$$

Quality control function (7) minimizes power consumption.

$$Q_2(P_1, P_2, P_3) = |P_x| \rightarrow \max. \quad (8)$$

The quality control function (8) implements the maximum control action in the positive or negative directions of the axis OX_1 , respectively, which allows you to create the maximum speed of longitudinal movement and reduce the time for longitudinal movement.

$$Q(P_1, P_2, P_3) = |P_y| \rightarrow \max. \quad (9)$$

The control quality function (9) implements the maximum control action in the positive or negative directions of the axis OY_1 , respectively, which makes it possible to create the maximum speed of lateral movement and reduce the time for lateral movement.

$$Q_2(P_1, P_2, P_3) = |M_z| \rightarrow \max. \quad (10)$$

The control quality function (10) implements the maximum control torque around the axis OZ_1 in the positive or negative directions, respectively, which allows you to create the maximum angular rotation speed in the yaw channel and reduce the turnaround time.

Unfortunately, it is not possible to obtain an analytical solution to the considered optimization problem. Therefore, further study of the structure was carried out by numerical methods in the MATLAB environment. For this, the numerical optimization procedure Optimtool of the Optimization Toolbox library was used.

The problem of finding the optimal control $P_1(n), \alpha_1(n), P_2(n), \alpha_2(n), P_3(n)$ at the n -computation step is reduced to solving the problem of minimizing the control quality function (7) in the fuel saving mode or maximizing the control quality functions (8)–(10) in the mode of maximum positioning accuracy, in the presence of constraints such as equalities (4)–(6) and inequalities (3). This optimization problem should be solved in the on-board controller of the control system in real time, therefore, the time for its solution should not be large and should be placed in on-board controller cycle with the time for solving other tasks. For nonsmooth functions, more complex global optimization methods are used, for example [14–16]. In our case the control quality functions (7) or (8)–(10) are smooth, the search for the optimal solution does not present much difficulty and can be carried out in a small number of iterations. To further reduce the search time for the optimal solution $P_1(n), \alpha_1(n), P_2(n), \alpha_2(n), P_3(n)$ at the n -computation step, it is proposed to take the optimal solution $P_1(n-1), \alpha_1(n-1), P_2(n-1), \alpha_2(n-1), P_3(n-1)$ from the previous computation step as an initial approximation.

To solve the optimization problem, the function was selected from Optimization Toolbooks library

$$\text{fmincon}(@\text{fun}, \mathbf{x}(0), \mathbf{A}, \mathbf{b}, \mathbf{Aeq}, \mathbf{beq}, \mathbf{lb}, \mathbf{ub}, @\text{nonlcon}),$$

where (@fun is the link to file with optimization function (7) or (8)–(10),

$\mathbf{x}(0)$ is the initial approximation vector,

$\mathbf{A} = \square$ is the matrix of the inequalities type linear constraints system, is absent,

$\mathbf{b} = \square$ is the right-hand side vector of the inequality type linear constraints system, is absent,

$\mathbf{Aeq} = \square$ is the matrix of the equality type linear constraints system, is absent,

$\mathbf{beq} = \square$ is the right-hand side vector of the equality type linear constraints system, is absent,

$\mathbf{lb} = [-P_1^{\max}, -\pi, -P_2^{\max}, -\pi, -P_3^{\max}]$ is lower bound vector,

$\mathbf{ub} = [P_1^{\max}, \pi, P_2^{\max}, \pi, P_3^{\max}]$ is upper bound vector,

@nonlcon is the link to a file of the equalities type nonlinear constraints (4)–(6).

Fig. 2 shows the results of mathematical modeling of dynamic positioning processes in the MATLAB environment in the form of graphs in time of the state vector parameters: longitudinal speed V_x , longitudinal displacement X_g , lateral speed V_y , lateral displacement Y_g , angular rate in the roll channel ω_x , roll angle φ , yaw rate ω_z and yaw angle ψ . The blue graphs correspond to the optimal control with the control quality function Q_2 , and the red graphs correspond to the equal-module control with orthogonal vectors. In the time interval (0–20) sec, a gust of wind acts on the vessel at a speed of 20 m/s at an angle of 45° to the diametrical plane, which leads to deviations of the parameters of the state vector from their programmed values. Moreover, the deviation $\Delta X_g = 0,6$ m, $\Delta Y_g = -2$ m for optimal control and $\Delta X_g = 1,0$

m , $\Delta Y_g = -3$ m for equal-modulus control with orthogonal vectors. Thus, the results of mathematical modeling confirm an increase in the dynamic positioning accuracy in the longitudinal channel on $\delta_x = \frac{1-0,6}{1}100\% = 40\%$ and in the transverse channel on $\delta_y = \frac{-2+3}{3}100\% = 33\%$ when using the optimal control.

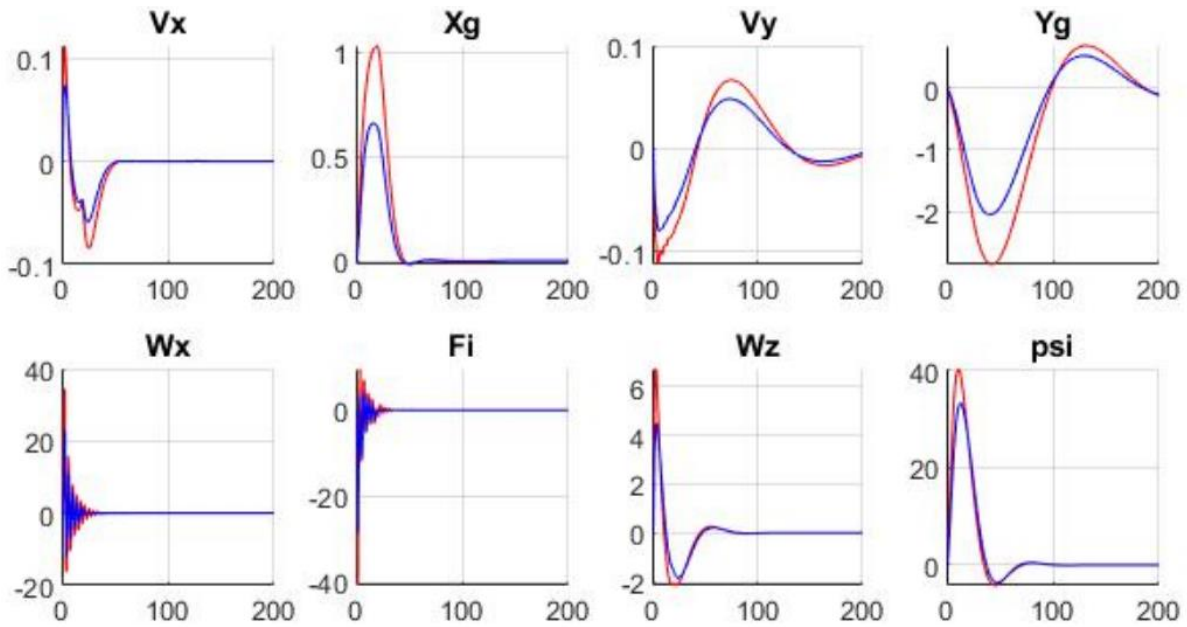


Fig. 2 – Results of mathematical modeling of dynamic positioning processes

Conclusion. The article considers the issues of automatic control of the vessel movement with a redundant control structure. Several schemes for splitting control into executive devices of a redundant structure, including an optimal splitting scheme, are considered. A comparative analysis of the considered splitting schemes with the optimal one is carried out. Comparative analysis showed that the use of optimal control of the redundant structure of actuators allows increasing the accuracy of dynamic positioning by (20–40) %, depending on the direction of the created control, as well as reducing fuel consumption by (30–100) %, which determines its advantages over known solutions. The mathematical and software support for an automatic optimal control system with redundant control has been developed. The operability and efficiency of the mathematical and software support were tested in a closed circuit with a control object in the MATLAB environment and Imitation Modeling Stand [17, 18]. The conducted experiments confirmed the operability and efficiency of the developed method, algorithms and software and allow to recommend them for practical use in the development of vessel control systems with redundant control structures.

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