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Marine ship's course stabilization based on an autopilot with a simple fuzzy controller

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Abstract. A simple method for generating a fuzzy course controller for a marine ship is presented. The controller is built without using training data. The new fuzzy controller uses conventional triangular sets, no complex overlaps, no complex expert judgments inherent in other types of fuzzy controllers. This approach makes it possible to synthesize a controller based on unified rules. The system is not hybrid and does not use other methods such as neural networks and reference models. The applicability of the proposed approach is demonstrated by an application for controlling the course of a marine ship in various modes. It is shown by means of simulation that the exchange rate stabilization system synthesized with the new fuzzy controller has robust properties.
Keywords: fuzzy controller, fuzzy-PID control, marine autopilots, robust system, ship control.

1. Introduction

The task of automatic navigation of the ship along the route is solved by onboard control systems. They are called *Track Control Systems* (TCS) and control the course and lateral deviation from the given track line, compensating for drift. The *Course control system* (CCS) is called «Autopilot» [1–5]. Solving the problems of improving the operational characteristics of marine ships with a simultaneous increase in the safety of navigation led to the creation of various types of *Course stabilization systems* (CSS) for marine ships – autopilots [3–6]. At the same time, the technical implementation of a modern autopilot of a marine ship must meet international requirements (*IMO Res*. A.342 (IX), *IMO Res*. *MSC*. 64 (67) *Annex* 3, *IMO Res*. *A*694 (17), *IMO Res*. *A*. 822 (19) i *ISO*11674 (2006) / 16329 (2003) *for High Speed Crafts*, *IEC* 62065 *Track Control System*).

A significant contribution to the development of methods of control, identification of parameters, driving along the route and modeling the movement of ships was made by (retrospectively) *Davidson K. S., Nomoto K., Norrbin N. H., Abkowits M. A., Chislett M., Bellman R. E., Bech M. I., Åström K. J., Källström C. G, Ogawa A., Kose K., J. van Amerongen, Duetz H., Hara K., Webster W. C., Paulsen M. J., Fossen T. I., Lisowski J., Sorensen A.J., Strand J. P., Bar-Shalom Y., Thomas B. S., Tomera M., Zwierzewicz Z., Nielsen U. D.* [7–31].

On the basis of theoretical and experimental researches of these and other scientists, various types of autopilots have been created [3–5, 32–39]. A modern autopilot must:

a) automatically keep the ship on a given course with an accuracy at which the average value of the course can differ from the given course only by a predetermined angle and at a speed that ensures stable controllability of the ship;

b) the maximum amplitude of the risk should not exceed the allowable for manual control;

c) the autopilot must ensure the automatic keeping of the ship on a given course with a minimum load on the steering gear (SG) in terms of the magnitude and number of rudder shifts.

Thus, the main tasks of an autopilot marine ship are to automatically keep the ship on a given course, ensure the ship's transition from course to course with a given angular velocity or radius, control, together with the built-in electronic charting navigation and information system (ECNIS), the movement of the ship along a given trajectory.

But marine ships are non-linear systems in terms of their control. Any changes in the speed of the ship, its draft or mass lead to significant changes in the dynamic parameters of the ship. In addition to control disturbances, the ship is affected by wind, waves, current, which leads to deviations from the set course.

These influences significantly complicate the problems of exchange rate stabilization. In the works of these and many other researchers, it is shown that the autopilot must have the ability to manually and/or automatically adjust to changes in the dynamic characteristics of ships under changing weather conditions, changing ship loading, etc.

A typical autopilot's structure always contains a course stabilization controller l acting on the ship's steering gear. Most controllers of modern autopilots use PID control algorithms and have the ability to manually and/or automatically change the PID settings.

Autopilots with PID controllers also have settings for changing the dead zone along the course and direction. Despite this, the resulting quality of ship's course control processes is often less than desirable, causing fuel waste and steering gear wear. These effects are especially noticeable for small displacement ships, whose sensitivity to disturbances and regulator (controller) settings is much greater than for large ships.

The main disadvantages of course stabilization systems with PID algorithms is the difficulty of simultaneously achieving the required control accuracy, stability and rapidity. Therefore, when synthesizing SSC, it is necessary to make compromise decisions: to choose the changing parameters of the controller in such a way as to ensure the necessary accuracy of maintaining the course with the necessary margin of stability.

Based on these shortcomings and taking into account the current stage of development of self-tuning SSCs, it can be concluded that the increase in the efficiency of their work by retuning the PID-controller coefficients has actually been exhausted. The need for a tangible increase in the efficiency of ships in the course stabilization mode requires a revision of the laws of governance and the structures of existing systems.

Various course control methods of ships are known [5, 34–38], which are attempts to improve the quality of course stabilization processes.

Fuzzy logic controllers are considered to be a fairly reliable solution, allowing them to cope with changes in the dynamics and state of the ship. Based on fuzzy set theory [40–47], marine uses have been found, including submarines, warships, and torpedoes and others. Of the autopilots in use today, a significant part can be found on small ships.

The main problem of using fuzzy controllers for course stabilization is not the technical side of the problem, but the algorithmic one, associated with the compilation of the rule base, fuzzification and defuzzification [40]. The solution of these problems requires the involvement of experts in each specific case and always implies subjectivity in the final decision.

A modern marine ship is a complex technical system. There are many urgent scientific and technical problems of increasing the efficiency and safety of the operation of marine ships [48–51]. It is possible to single out the main tasks of increasing the efficiency of ship operation by means of control systems:

– ensuring the movement of the ship on a given trajectory;
– keeping the ship on a given course in conditions of changing weather factors;
– keeping the ship on a given course in conditions of limited maneuver and high traffic intensity;
– automatic correction of the selected path and speed.

2. Theoretical prerequisites for solving the problem of marine ship's course stabilization

The task of course stabilization is reduced to a system containing, in addition to the course controller and feedback sensor (for example, a gyrocompass), the control object is a marine ship. IMO (*International Maritime Organization*) developed and adopted resolution A.751(18). The resolution regulates the need to use mathematical models of the ship in solving practical problems related to the safety of navigation. At the 14th International Conference of Experimental Pools, simplified mathematical models of the ship – Nomoto models of the first and second order were recommended for practical use in autopilots. The Nomoto model of the first order is extremely simplified and is used for verification (evaluative, preliminary) calculations of regulator settings

The second order Nomoto model [52–54] is more efficient in practice and is described by the differential equation:

$$T_1 \cdot T_2 (d^2\omega/dt^2) + (T_1 + T_2)(d\omega/dt) + \omega + H(\omega) = K \cdot \alpha_r + KT_3(d\alpha_r/dt),$$

where ω – angular frequency (speed) of the ship; $H(\omega) = \nu_1|\omega|\omega + \nu_2\omega^3$ – the nonlinear function of the angular frequency; T_1, T_2, T_3, K, ν_1, ν_2 – the parameters of the mathematical model; α_r – rudder angle.

One of the simple solutions to this problem of identifying the parameters of equation (1) is presented in [55–58].

The need to change the parameters of the PID-controller settings is due to the fact that with a change in the linear speed of the ship, its draft or mass, the parameters of the mathematical model will also change significantly – T_1, T_2, T_3, K, ν_1, ν_2.. Depending on the specific operating conditions of the ship, some of these parameters may vary from 0.7 to 1.8 times relative to the accepted nominal value. It is because of these changes in the parameters of the ship that it is necessary to readjust the parameters of the course controller.

Fuzzy controllers (FC) with symmetric triangular membership functions and singleton fuzzification and defuzzification methods (centre of gravity method) are universal approximators [59]. That is why fuzzy control has robust properties, which is very important for controlling objects with changing parameters, such as marine ships.

The technical implementation of fuzzy controllers must comply with IEC *IEC* 61131-7, Part 7. Fuzzy logic standardization. This is necessary to ensure hardware compatibility. The principles of synthesis of fuzzy control algorithms are fixed in *IEC* 61131-3. Compliance with the requirements of the *IEC* 61131-7 standard limits the variety of solutions when creating an FC, significantly simplifying the task of designing a controller. This standard defines: blurring (*fuzzification*), inverse compaction (*defuzzification*), rules for operations of association (*agreggation*), activation (*activation*), accumulation (*accumulation*). The standard also defines the basic commands of the *Fuzzy Control Language* (FCL) for control systems with fuzzy logic. Note that the implementation of FC can be both hardware and software (*Siemens, Fuji Electric, Motorola, Intel, Allen-Bradley* and others). Controllers often use specialized *Fuzzy Chips* and *Fuzzy Processors* (*Adaptive Logic,* 68*HCxx, MCS*-96, *FUZZY*-166 and others).

According to the *IEC* 61131-7 standard, the FC functional diagram contains the following nodes: fuzzification, logic conclusion with a rule base, defuzzification. The most common is the following sequence of processing input variables by a fuzzy controller $\bar{x}$ [40–47].

Fuzzification is carried out for at least two input variables. At the stage of fuzzification (transformation of clear input variables into their fuzzy, linguistic, values), the range D of change in input variables $\bar{x}$ is divided into sets (small negative – *NS*, zero – *Z*, small positive – *PS*, etc.). The degree of belonging of the variables to the set is determined by the membership functions (MF) to the set $\mu_j(\cdot)$ that satisfy the consistency condition for any x_i: $\sum^{j} \mu_j(x_i) = 1$.

The variables $\bar{x}$ are converted with the help of the MF into the corresponding logical variables $\mu(\bar{x})$, and all input variables are considered to be independent samples. When transforming logical variables, a logical conclusion based on the rule base is carried out. The rule base is formulated in each specific case by subject matter experts. For example, experts in the field of navigation – qualified captains of marine ships. The set of fuzzy rules $\overline{A} \Rightarrow \overline{B}$, in the general case, is written as

$$IF\ (x_1 \in A_1)\ AND \ldots (x_j \in A_j)\ AND \ldots (x_n \in A_n)\ THEN\ (y \in B_i) \cdot \tag{1}$$

The implementation of transformations 1 (1) requires finding the MF. The simplest case of representation of logical variables is the control error $x_1 = \varepsilon$ and its derivative $x_2 = s \cdot \varepsilon$ with triangular MFs, where s – differentiation operator. The operation *AND* in 1 (1) corresponds to the intersection of sets, and the result of applying all the rules corresponds to the operation of union (aggregation) of sets. If the rule is formulated:

$$IF\ (\varepsilon \in NS)\ AND\ (s \cdot \varepsilon \in PS),\ THEN\ (y \in ZE),$$

then the MF for the intersection of two sets *NS* and *PS* is written as $\mu_{\varepsilon \cap s \cdot \varepsilon} = \min(\mu_\varepsilon,\ \mu_{s \cdot \varepsilon})$, and the union – $\mu_{\varepsilon \cup s \cdot \varepsilon} = \max(\mu_\varepsilon,\ \mu_{s \cdot \varepsilon})$.

The membership functions, for each of the sets included in the fuzzy output variables $\overline{y}$ in the rules (1) are obtained in the form

$$\begin{cases} \mu_{Rul.1}(\overline{y}) = \min\{\mu_{y_1}(\overline{y}), \min(\mu_{\varepsilon_1}(\varepsilon), \mu_{s \cdot \varepsilon_1}(s \cdot \varepsilon))\}; \\ \ldots \\ \mu_{Rul.j}(\overline{y}) = \min\{\mu_{y\,j}(\overline{y}), \min(\mu_{\varepsilon\,j}(\varepsilon), \mu_{s \cdot \varepsilon\,j}(s \cdot \varepsilon))\} \end{cases}, \tag{2}$$

moreover, the rules containing the same consequences and related to the same interaction are combined into one, and the resulting MF of the output action, after applying all the rules included in 2, is found by aggregation:

$$\mu(\overline{y}) = \max\{\mu_{Rul.1}(\overline{y}), \ldots, \mu_{Rul.j}(\overline{y})\}. \tag{3}$$

Transforming the result (3) into an output signal is defuzzification. The result is achieved by defining the «center of gravity» $\overline{y}_c$ for $\mu(\overline{y})$ [37]:

$$\overline{y}_c = \frac{\int_{y_{\min}}^{y_{\max}} \mu(\overline{y}) \cdot \overline{y}\, dy}{\int_{y_{\min}}^{y_{\max}} \mu(\overline{y})\, dy}. \tag{4}$$

Modern fuzzy microcontrollers have full support for input/output of variables, unified command systems for all stages of fuzzification, logical conclusion and defuzzification. These properties of the controllers make it possible to implement almost any fuzzy control algorithms for a marine ship in course stabilization modes. But the main function of FC – fuzzification, still does not have an unambiguous solution.

3. Synthesis of fuzzy controller

The main difficulty in the synthesis of a fuzzy course controller for a marine ship lies in the development of an effective base (table) of rules. For example, the implementation of a fuzzy course PID-controller requires a 3D table entry. Recording a rule table, even with the help of expert navigators, is particularly difficult to formalize for the control of a marine ship under various operating conditions. It is for this reason that FCs can be multi-loop systems containing, for example, separate P-, I- and D-loops [41–44].

A dual-loop controller is presented, containing two FCs – F_1 and F_2 (Fig. 1). The controller contains two inputs and one output per loop. We consider that the transfer functions $W_{11}(s)$, $W_{21}(s)$ and $W_{12}(s)$, $W_{22}(s)$ of the input signals (terms) $\bar{x}$ are proportional links; there are two input signals – $x_{11}(s) = x_{12}(s)$ and $x_{21}(s) = x_{22}(s)$, the first of them is the control error $\varepsilon(s)$, and the second is the derivative $s\cdot\varepsilon(s) \Rightarrow d\varepsilon(\tau)/d\tau$ from error; the transfer function $W_{31}(s)$ of the first FC performs a proportional gain, and the second FC $W_{32}(s)$ – the operation of integration with the time constant T_i; nonlinear transfer coefficients K_{1F1}, K_{2F1} and K_{1F2}, K_{2F2} of fuzzy controllers for each of the terms $x_1(s)$, …, $x_4(s)$ are linearized. Then:

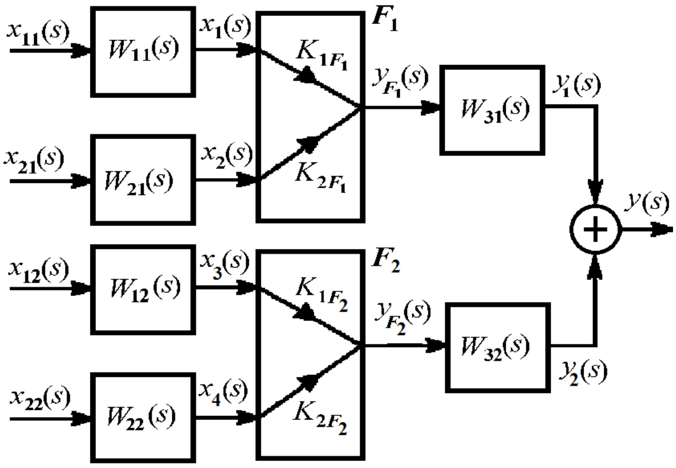

Figure 1. Dual-loop controller

$$\begin{cases} W_{11}(s) = k_{P1}; \quad W_{21}(s) = k_{D1}; \\ W_{12}(s) = k_{P2}; \quad W_{22}(s) = k_{D2}; \\ \varepsilon(\tau) \Rightarrow \varepsilon(s) = x_{11}(s) = x_{12}(s); \\ d\varepsilon(\tau)/d\tau \Rightarrow s\cdot\varepsilon(s) = x_{21}(s) = x_{22}(s); \\ K_{1F1} = \dfrac{\partial F_1(\tau)}{\partial x_1(\tau)}; \quad K_{2F1} = \dfrac{\partial F_1(\tau)}{\partial x_2(\tau)}; \\ K_{1F2} = \dfrac{\partial F_2(\tau)}{\partial x_3(\tau)}; \quad K_{2F2} = \dfrac{\partial F_2(\tau)}{\partial x_4(\tau)}; \\ W_{31}(s) = k_p; \quad W_{32}(s) = \dfrac{1}{s\cdot T_i}, \end{cases} \tag{5}$$

where k_{P1}, k_{P2}, k_{D1}, k_{D2} – proportional and differential coefficients, respectively.

From (5), according to Fig. 1, we get:

$$\begin{cases} y_1(s) = \varepsilon(s)\cdot k_{P1}\cdot K_{1F1}\cdot k_P + s\cdot\varepsilon(s)\cdot k_{D1}\cdot K_{2F1}\cdot k_D; \\ y_2(s) = \varepsilon(s)\cdot k_{P2}\cdot K_{1F2}\cdot \dfrac{1}{s\cdot T_i} + \varepsilon(s)\cdot k_{D2}\cdot K_{2F2}\cdot \dfrac{1}{T_i}; \\ y(s) = y_1(s) + y_2(s), \end{cases} \tag{6}$$

whence the transfer function FC

$$W_{FC}(s) = \frac{y(s)}{\varepsilon(s)} = k_{P1}\cdot K_{1F1}\cdot k_P + k_{D2}\cdot K_{2F2}\cdot \frac{1}{T_i} + k_{P2}\cdot K_{1F2}\cdot \frac{1}{s\cdot T_i} + s\cdot k_{D1}\cdot K_{2F1}\cdot k_D \tag{7}$$

corresponds to the transfer function of an ideal PID-controller:

$$W_{FC}(s) = K_{pFC} + \frac{1}{s\cdot T_{iFC}} + s\cdot T_{\partial FC}, \tag{8}$$

where $K_{pFC} = k_{P1} \cdot K_{1F1} \cdot k_P + k_{D2} \cdot K_{2F2} \cdot \dfrac{1}{T_i}$; $T_{iFC} = T_i / (k_{P2} \cdot K_{1F2})$; $T_{\partial FC} = k_{D1} \cdot K_{2F1} \cdot k_D$.

We accept that the input signals are divided into 5, and the output into 7 sets. Without resorting to the help of experts, we formalize the record of the controller output rules. Let's present the set of rules (1) in tabular form for, for example, one of the FC loops – proportional (see Fig. 2). To do this, we use the principle of symmetrical writing of the logical conclusion proposed by the authors: by turning the column of the variable x_2 vertically in comparison with the generally accepted representation for the directions of the columns of tables [41–47]. Such a table of rules is monotone.

It is obvious that the rules written in the center of the table (cells 1, 2, ... , 9 of the table shown in Fig. 2) provide a steady and close to it mode of operation. This increases the stability of the closed system and takes into account the fulfillment of the obvious condition $\varepsilon \cdot s{\cdot}\varepsilon < 0$ for the steady state (at $\varepsilon \in ZE$ and $s{\cdot}\varepsilon \in ZE$, $\varepsilon \to 0$ and $s{\cdot}\varepsilon \to 0$). All other rules (cells of the table) provide transitional modes of the stabilization system.

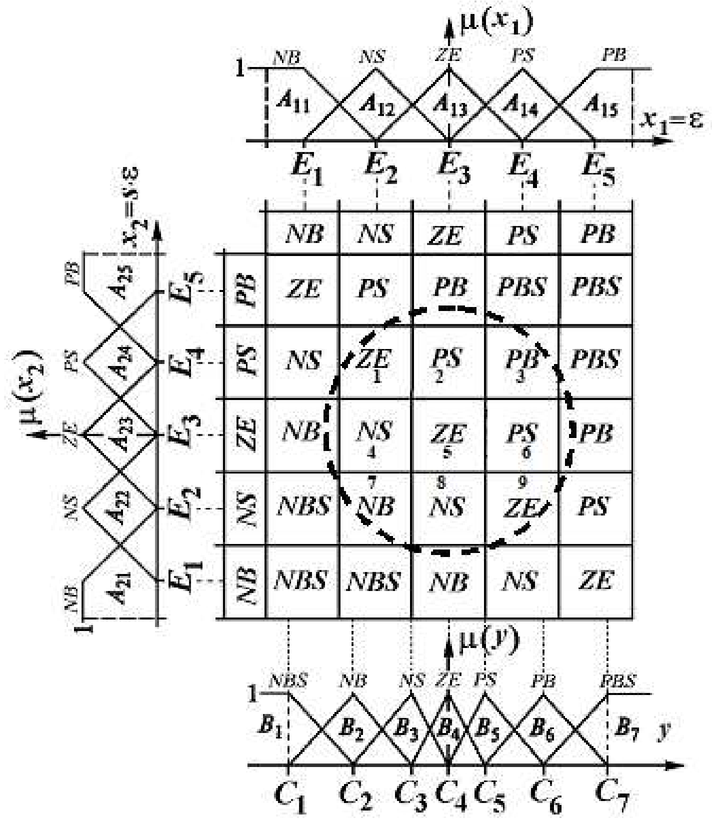

Figure 2. Membership functions and a symmetric table of rules for the developed FC

The specified properties of the FC with the proposed table of rules and MF are proved by the results of modeling the operation of the ship's course stabilization system (hereinafter, p. 4).

In any technical control system, the output signals of the sensors are always normalized (for example, to the level of ± 10 V). Therefore, the control signals are also normalized to the level of ± 10 V, and the output signal x_2 (derivative of the error ε) cannot exceed ± 10 V either. Thus, we can assume that the FC scale coefficients $k_{Pi} = k_{Di} = 1$ (see Fig. 1).

It is easy to determine for two input unbiased symmetric triangular terms and a biased output triangular term (see Fig. 3) the coefficients K_{1Fi} and K_{2Fi} FC. These coefficients are easily calculated as the ratio of the increments of the output signals $\bar{y}$ FC to the increments of the input signals $\bar{x}$, for small deviations of the terms from the steady motion, i.e. near the stabilization mode of the output coordinate of the control system. Let us take into account that the FC under consideration has two inputs and one output, and for any combination of input fuzzy singletons, the implication result will be nonzero only for four «active» rules.

If we calculate the HP gain coefficients K_{1F1} for the entire range of changes E_1 ... E_5 of input signals and take into account that the rule table and output terms are symmetrical, the input terms are also symmetrical and their number is equal, then we get $K_{1F1}= K_{2F2}$. For example, for $x_{21}\to E_3$ we get $K_{1F_1}=\frac{\partial \Delta y}{\partial \Delta x}\to\infty$. This means that with infinitely small input signals, the transmission coefficient FC tends to an infinitely large value, thus, near the stabilization point of the output variable, the control system becomes astatic.

If you install in each of the loops of the dual-loop fuzzy PID-controller (see Fig. 1), two absolutely identical FCs with the same scale coefficients k_{Pi} и k_{Di}, then the resulting block diagram can be simplified by eliminating the FC in one of the loops (see Fig. 3).

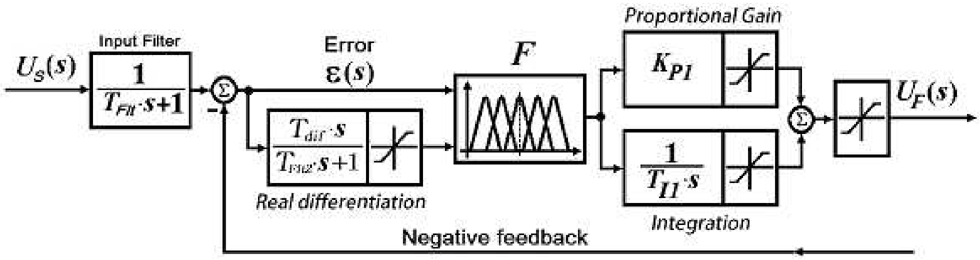

Figure 3. Block diagram of the fuzzy PID-controller

Using the similarity of expressions (7) and (8), one can abandon the method of adjusting the FC by «expert selection» of its parameters. In this case, the parameters of the PID-controller calculated for nominal operating conditions are taken as a basis, for example, providing the «technical» optimum.

Below is a model of the ship's course stabilization system and the results of its simulation in various conditions. An analysis of the results (p. 4) of the simulation proves that with the proposed formal writing of the rules (see Fig. 2), the marine ship's course stabilization system exhibits robust properties.

4. Synthesis a course stabilization system

4.1 System block diagram

The block diagram of the exchange rate stabilization system is well known [32–43, 60–62] and is shown in Fig. 4.

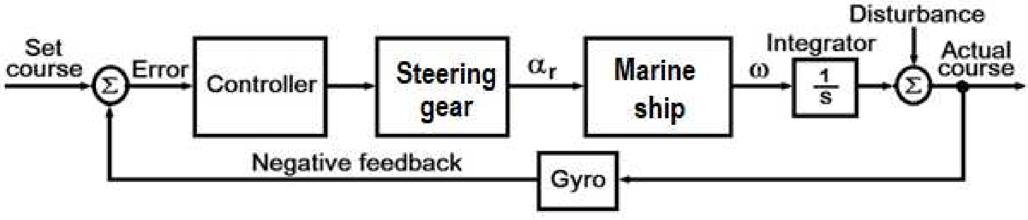

Figure 4. Block diagram of the stabilization system

A high-speed universal boat with a displacement of 480 tons was chosen as the object of modeling. The steering system is equipped with a low-inertia electric steering device [63, 64]. In this device, there are practically no restrictions on the frequency of turning the steering wheel, which allows you to create highly efficient autopilots. The maximum steering angle is ± 45°.

4.2. Transfer functions and parameters of the block diagram of the system

The identification of the parameters of expression (1) is carried out on the basis of [55], using [54, 56–58].

As a result, the following parameters of the transfer functions of the stabilization system are accepted for modeling

a) *Steering gear*

$$W_{SG}(s) = \frac{15}{0{,}25s + 1}.$$

At the output, the function of limiting the output signal is ± 45° is additionally introduced.

b) *Marine ship* (1)

1) The nominal mode of movement of the ship. Ship loading with cargo is 60 %:

$$W_{\text{nom}}(s) = \frac{1{,}1s + 1}{50s^2 + 15s + [1 + H_1(s)]}. \quad (9)$$

2) Ship movement mode when the ship

$$W_{\min}(s) = \frac{0{,}5s + 1}{15s^2 + 8s + [1 + H_2(s)]}. \quad (10)$$

3) Ship movement mode when the ship is loaded with 100 % cargo:

$$W_{\max}(s) = \frac{2{,}0s + 1}{200s^2 + 30s + [1 + H_3(s)]}. \quad (11)$$

The coefficients K, ν_1, ν_2, included in the expressions $H_1(s)$, $H_2(s)$ and $H_3(s)$, practically do not change depending on the loading mode of the ship. Therefore, they are accepted as unchanged for any operating conditions of the ship ($K = 0{,}8$, $\nu_1 = -0{,}0112$, $\nu_2 = 0{,}0016$). The modeling of the nonlinear transfer functions $W_{\text{nom}}(s)$, $W_{\min}(s)$ and $W_{\max}(s)$ is based on the structural transformations given in [55, 65].

c) Negative feedback on the current course of the ship

$$W_{NF}(s) = \frac{1{,}0}{0{,}1s + 1}.$$

d) Wind-wave disturbances

Disturbances that deviate the ship's course from the set value are described by the sum of four sinusoidal signals of different amplitude, frequency and phase. Their resulting action is shown in Fig. 5.

e) Controllers

1) *Proportional-integral controller*

To evaluate the robustness properties of the ship's course stabilization system, the PID-controller parameters are unchanged for any changes in the transfer functions $W_{\text{nom}}(s)$, $W_{\min}(s)$ and $W_{\max}(s)$ of the ship model. The calculation of the PID-controller tuning parameters (with output signal limitation at the level of ± 10 V) was carried out for the nominal transfer function $W_{\text{nom}}(s)$. Tuning requirements:

overshoot no more than 2° and minimum transient time. For these conditions and $W_{\text{nom}}(s)$, the PID-controller transfer function $W_{\text{PID}}(s) = P + I/s + D\frac{N}{1 + N/s}$, has the following tuning values.

Proportional: P = 0,01. Integral: I = 0,0013 s^{-1}. Derivative: D = 0,1 s. Filter coefficient: N = 0,7.

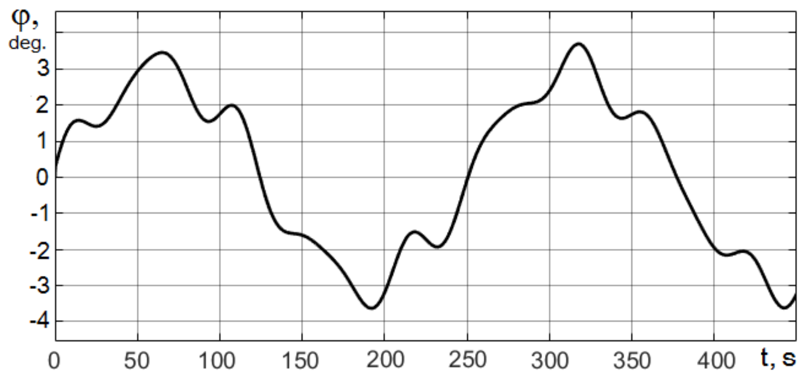

Figure 5. The shape of the disturbing signal

2) *Fuzzy controller*

The controller model is based on Fig. 2, Fig. 3 and built-in *Fuzzi Tech Matlab* algorithms. According to Fig. 3 the following parameters are taken.

Input filter. Time constant T_{Flt} = 0,05 s. Real differentiation filter. Time constant T_{Flt2} = 0,01 s.

The main parameters of the controller. Proportional: K_{P1} = 0,012. Integral time constant: T_{I1} = 10^4 s. Derivation time constant: T_{dif} = 0,1 s.

5. Simulation results and discussion

The modeling of course stabilization processes was carried out at a constant linear speed of the ship (25 km/h).

a) When using a PID-controller in the system and in the absence of wind-wave disturbances, the processes of changing the ship's course with its subsequent stabilization are obtained.

At the time t = 50 s, the command to change the course to increase up to + 10°occurred, at the time t = 250 s the course changed again by +10°, up to a value of 20° (see Fig. 6).

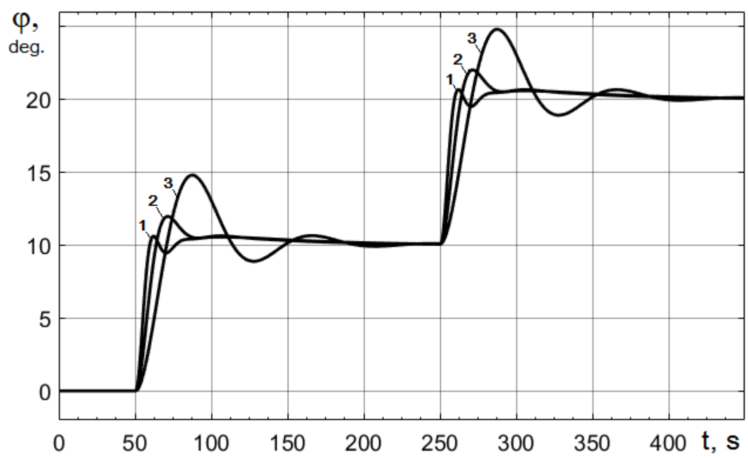

Figure 6. Processes in the course stabilization system with a PID-controller in the absence of disturbances

Graph 2 shown in Fig. 6 corresponds to the nominal operating mode of the ship, calculated for the transfer function (9). Graph 1 corresponds to the mode of movement of the ship when the ship is loaded with cargo by 20 % – according to the transfer function (10). Graph 3 corresponds to the mode of movement of the ship when the ship is loaded with cargo by 100 % – the transfer function (11). The overshoot in this case is 5°, which exceeds the specified requirements for the quality of the transient process. The control time is also significantly increased. Obviously, in this mode, it is necessary to manually reconfigure the PID-controller parameters.

On Fig. 7 shows similar processes for changing and stabilizing the ship's course. However, in this course stabilization system, a fuzzy controller functions (see Fig. 3), with a symmetrical rule table and membership functions shown in Fig. 2.

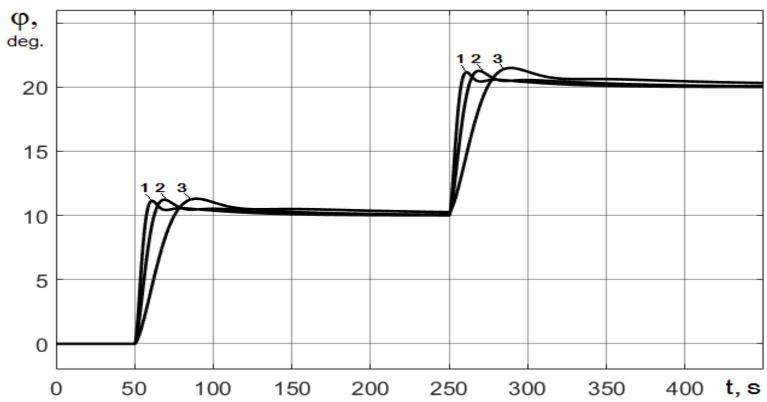

Figure 7. Processes in the course stabilization system with a fuzzy controller (Fig. 2, Fig. 3) in the absence of disturbances

Graph 2 shown in Fig. 7 corresponds to the nominal operating mode of the ship, calculated for the transfer function (9). Graph 1 corresponds to the mode of movement of the ship when the ship is loaded with cargo by 20 % – according to the transfer function (10). Graph 3 corresponds to the mode of movement of the ship when the ship is loaded with cargo by 100 % – the transfer function (11). Analysis of the results shows that in any operating mode of the ship, the quality of transient processes (compared to similar modes for a system with a PID-controller) has increased significantly. The overshoot does not exceed 1.5° with a noticeable decrease in the regulation time.

The results of modeling the stabilization system (PID-controller and fuzzy controller) under the action of wind-wave disturbances on the ship's hull (see Fig. 5) are shown in Figs. 8 and Fig. 9.

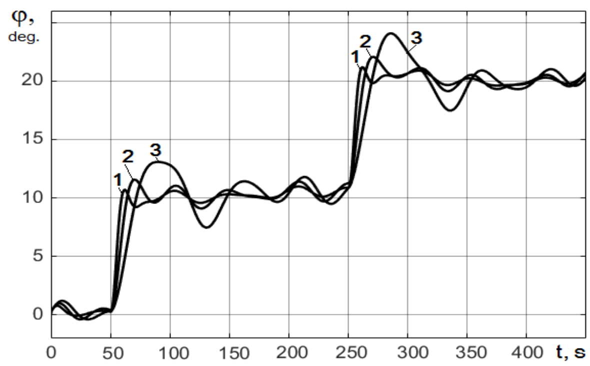

Figure 8. Processes in the course stabilization system with a PID-controller under the action of disturbances (see Fig. 5)

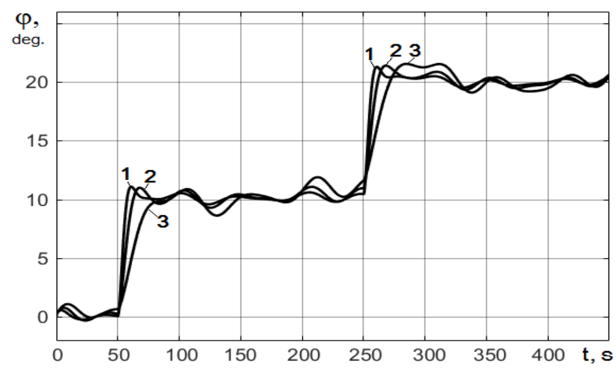

Figure 9. Processes in the course stabilization system with a fuzzy controller under the action of disturbances (see Fig. 5)

Comparison of the processes shown in Fig. 6 and Fig. 7, in Fig. 8 and Fig. 9 allows us to conclude that the system with the proposed fuzzy controller has robust properties and effectively stabilizes the given course of the ship.

6. Conclusion

For the course angle stabilization loop of a marine ship, the use of dual-loop fuzzy controllers is proposed, which implement the properties of the PID-controller in the nominal mode. It is proposed to combine several fuzzy controllers into a batch (parallel) fuzzy controller.

The installation of fuzzy controllers with the same type of symmetrical tables of rules leads to the almost complete elimination of oscillations in the stabilization system. Despite the properties of the controlled object (ship) that change depending on the operating mode, regardless of the given value of the course angle, the proposed system provides a high quality of stabilization processes. The robustness properties of the course angle stabilization system are enhanced by the use of a symmetrical rule table in fuzzy controllers.

The simulation results show that the proposed formalized method for writing a logical inference and the structure of the fuzzy controller make it possible to effectively stabilize the course angle of a marine ship. As a result of modeling studies, it is shown that the proposed fuzzy controller provides the asymptotic stability of the system as a whole, as well as the robustness of the system from the side of a limited range of parameter changes and disturbances of the control object.

In further researchs, it is supposed to prove the enhancement of the robustness properties of the course angle stabilization system by reducing the number of inference rules and by shifting the centers of membership functions of the fuzzy controller near steady-state modes.

References

[1] Roberts G 2008 Trends in marine control systems *Annual Reviews in Control* 32 (2) pp 263–269

[2] Golnaraghi F and Kuo B C 2010 Automatic Control Systems (Wiley) p 786

[3] Tomera M 2010 Nonlinear controller design of a ship autopilot *Int. J. Appl. Math. Comput. Sci* 20 (2) pp 271–280

[4] Zhang Xian-ku and Zhang Guo-qing 2016 Design of ship course-keeping autopilot using a sine function-based nonlinear feedback technique The Journal of Navigation (*Electronic Materials* vol 2) (Published online by Cambridge University Press) 69 pp 246–256

[5] Abrougui H, Dallagi H and Nejim S 2019 Autopilot design for an autonomous sailboat based on sliding mode control *Automat. Control Comput. Sci.* 53 (5) pp 393–407

[6] Wen-Hsien Ho, Chen-Huei Hsieh and Jyh-Horng Chou 2010 Optimal course handling control for nonlinear ship maneuvering system *International Journal of Innovative Computing, Information and Control ICIC, International* 6 10 pp 114–117.

[7] Davidson K S and Schiff L I 1946 Turning and course keeping qualities *Trans. Soc. of Nav. Architects Marine Eng.* 54 pp 152–200

[8] Nomoto K 1960 Analysis of Kempf's Standard Maneuver Test and Proposed Steering Quality Indices *Proceedings of 1st Symposium on Ship Maneuverability* pp 275–304

[9] Norrbin N H 1963 On the Design and Analysis of the Zig-Zag Test on Base of Quasilinear Frequency Response Technical Report B140-3 *The Sweden State Shipbuilding Experimental Tank* 14 pp 91–107

[10] Abkowits M A 1964 Lecture on ship hydrodynaics – steering and manoeuvrability. Hydro-Og Lab., Accession Number 00323500, Source Agency: *Stevens Institute of Technology*, Report/Paper Numbers HY-5 p 178

[11] Chislett M and Strom-Tejsen I 1965 Planar Motion Mechanism Tests and Full-Scale Steering and Maneuvering Predictions for Mariner Class Vessel, *Technical Report Hy-5*, Hyro and Aerodynamics Laboratory, Lyngby, Denmark p 215

[12] Bellman R E and Zdech L A 1970 Decision making in a fuzzy environment. *Manag. Sci.* 17 pp 141–164.

[13] Bech M I 1972 Some aspects of the stability of automatic course control of ships Proc. Int. Symp. on Directional Stability and Control of Bodies Moving in Water, *Journ. Mech. Enpineerinr Science* l4 (77) pp 123–131

[14] Åström K J and Wittenmark B 1973 On self-tuning regulators *Automatica* 9 pp 185–199

[15] Åström K J and Källström C G 1976 Identification of Ship Steering Dynamics *Automatica* 12 pp 9–22.

[16] Ogawa A and Kasai H 1978 On The Mathematical Model of Maneuvering Motion of Ship, *ISP* 25 (292) pp 306–319

[17] Kose K, Yumuro A and Yoshimura Y 1981 Concrete of Mathematical model for ship maneuverability *3rd*

Symposium on ship maneuverability, SNAJ pp 27–80
[18] Amerongen van J 1982 Adaptive steering of ships: a model-reference approach to improved maneuvering and economical course keeping: Ph.D. Thesis *Delft University of Technology. Delft: Technische Hogeschool Delft*. p. 211
[19] Duetz H 1989 An adaptive autopilot for inland ships *Adaptive Systems in Control and Signal Processing* pp 283–288
[20] Hara K 1990 On shipboard use of the intelligent ship concept for safe navigation *VI IMLA Conference, Bremen* pp 1–10
[21] Webster W C 1992 Shiphandling Simulation: Application to Waterway Design *National Press, Washington D C* p 151
[22] Paulsen M J, Egeland O and Fossen T I 1994 An output feedback controller with wave filter for marine vehicles *Proceedings of 1994 American Control Conference - ACC '94* 2 pp 2202–2206
[23] Lisowski J and Smierzchalski R 1995 Assigning of Safe and Optimal Trajectory Avoiding Collision at Sea *3rd IFAC Workshop Control Applications in Marine System, Trondheim-Norway* pp 346–350
[24] Sorensen A J, Adnanes A K, Fossen T I and Strand J P 1997 A New Method of Thruster Control in Positioning of Ships Based on Power Control *IFAC Proceedings* 30(22) pp 199–206
[25] Fossen T I 1999 Guidance and Control of Ocean Vehicles *John Wiley & Sons Ltd.* p 481
[26] Bar-Shalom Y, X.-Rong Li and Thiagalingam Kirubarajan 2001 Estimation with applications to tracking and navigation *New York: John Wiley & Sons*, 2001 p 526
[27] Thomas B S and Sclavounos P D 2007 Optimal control theory applied to ship maneuvering in restricted waters *Journal of Engineering Mathematics* 58 (1) pp 301–315
[28] Sorensen A J 2013 Marine control systems. Propulsion and motion control of ships and ocean structures: Lecture notes *Trondheim: NTNU press* p 536
[29] Tomera M 2014 Dynamic positioning system for a ship on a harbour maneuvering with different observers. Experimental results Polish marintime research 21 pp 13–24
[30] Zwierzewicz Z 2015 The design of ship autopilot by applying observer based feedback linearization *Pol. Marit. Res.* 22 (1) pp 16–21
[31] Nielsen U D 2017 Response prediction of vessel motions and sea state estimation from ships. *DTU Mechanical Engineering. NTNU AMOS*, p 351
[32] Fossen T I and Smogeli O N 2004 Nonlinear Time-Domain Strip Theory Formulation for Low-Speed Maneuvering and Station-Keeping *Modelling, Identification and Control*, *MIC* 25(4) pp 201–221
[33] Fossen T I 2005 A Nonlinear Unified State-Space Model for Ship Maneuvering and Control in a Seaway *Journal of Bifurcation and Chaos* (Plenary Talk ENOC'05, Eindhoven, The Netherlands) pp 355–361
[34] Sutulo S and Soares Guedes 2011 Mathematical Models for Simulation of Maneuvering *Performance of Ships Marine Technology and Engineering* (Taylor & Francis Group, London) pp 661–698
[35] Perez T and Fossen T I 2007 Kinematic Models for Sea-keeping and Maneuvering of Marine Vessels *Modelling, Identification and Control, MIC* 28 (1) pp 1–12
[36] Volyanskaya Ya Synthesis of mathematical model of controlled electromotive device of pilotless floating vehicle *IOP Conf. Series: Earth and Environmental Science* 172 (2018) 012008
[37] Perez T and Fossen T I 2006 Time-Domain Models of Marine Surface Vessels for Simulation and Control Design Based on Sea-keeping Computations (Plenary Talk) *Proc. of the IFAC* (MCMC'06, Lisbon, Portugal) pp 20–24
[38] Abrougui H, Nejim S, Hachicha S, Zaoui Ch and Dallagi H Modeling, parameter identification, guidance and control of an unmanned surface vehicle with experimental results *Ocean Engineering* 241 (2021) 110038
[39] Li H, Liu Ju and Liu R 2017 Dynamic speed control model for very large ship in restricted waters *Proceedings of the Twenty-seventh International Ocean and Polar Engineering Conference* (San Francisco, CA, USA, June 25–30, 2017) ISSN 1098-6189 pp 556–562
[40] Zadeh L A Fuzzy sets *Information and control* 8 (1965) pp 338–353; Similarity relations and fuzzy orderings *Information sciences* 3 (1971), pp. 177–200
[41] Zirilli A, Tiano A, Roberts G and Sutton R 2002 Fuzzy course-keeping autopilot for ships *IFAC Proceedings 15th Triennial World Congress* (Barcelona, Hispania) 35 (1) pp 355–360
[42] Velagica Ju, Vukicb Z and Omerdic E 2003 Adaptive fuzzy ship autopilot for track-keeping *Control Engineering Practice* 11 (4) pp 433–443
[43] Contreras Ju 2011 Generating fuzzy controllers for ship steering *IEEE Annual Meeting of the North American Fuzzy Information Processing Society* p 6
[44] Yunsheng F, Xiaojie S, Guofeng W and Chen G On fuzzy self-adaptive PID control for USV course *IEEE 34th Chinese Control Conference* (*Electronic Materials* ISSN: 1934-1768) (Hangzhou, China) pp 8472–8478

[45] Mu D, Zhao Yu, Wang G, Fan Yu and Bai Yu 2016 Course control of USV based on fuzzy adaptive guide control *IEEE Chinese Control and Decision Conference* (*Electronic Materials* ISSN: 1948-9447) (Yinchuan, China) pp 6433–6437
[46 Lin X, Nie Ju, Jiao Yu, Liang K and Li H 2018 Nonlinear adaptive fuzzy output-feedback controller design for dynamic positioning system of ships *Ocean Engineering* 158 pp 186–195
[47] Wang Yu, Wang H, Li M, Wang D and Fu M Adaptive fuzzy controller design for dynamic positioning ship integrating prescribed performance *Ocean Engineering* 219 (2021) 107956
[48] Melnyk O, Bychkovsky Y and Voloshyn A 2022 Maritime situational awareness as a key measure for safe ship operation *Scientific Journal of Silesian University of Technology. Series Transport* 114 pp 91–101
[49] Volyanskaya Y, Volyanskiy S, Volkov A and Onishchenko O 2017 Determining energy-efficient operation modes of the propulsion electrical motor of an autonomous swimming apparatus *Eastern-European Journal of Enterprise Technologies* 8 (90) pp 11–16
[50] Onishchenko O, Shumilova K, Volyanskyy S, Volyanskaya Y and Volianskyi Y 2022 Ensuring Cyber Resilience of Ship Information Systems *TransNav, International Journal on Marine Navigation and Safety of Sea Transportation* 16 (1) pp. 43–50
[51] Onyshchenko S and Melnyk O 2022 Efficiency of Ship Operation in Transportation of Oversized and Heavy Cargo by Optimizing the Speed Mode Considering the Impact of Weather Conditions *Transport and Telecommunication Journal* 23 (1) pp 73–80
[52] Nomoto K, Taguchi T and Hirano S 1957 On the steering qualities of ship *International Shipbuilding Progress* 4 35 pp 56–64
[53] Ayulia Sitio Agisjaihc 2010 An Analysis Nomoto Gain and Norbin Parameter on Ship Turning Maneuver *IPTEK, The Journal for Technology and Science* 21 (2) pp 307–309
[54] Agarkov S A, Pashentsev S V 2015 Parametric identification of the generalized Nomoto model using the apparatus of the calculus of variations *Bulletin of MSTU* 18 (1) pp 7–11
[55] Golikov V V, Golikov V A, Volyanskaya Ya, Mazur O and Onishchenko O A simple technique for identifying vessel model parameters *IOP Conf. Series: Earth and Environmental Science* 172 (2018) 012010
[56] Journée J M J 1970 A simple method for determining the maneuvering indices K and T from zigzag trial data *Delft University of Technology, Ship Hydromechanics Laboratory Report* p 267
[57] Casado M H, Ferreiro R and Velasco F J 2007 Identification of Nonlinear Ship Model Parameters Based on the Turning Circle Test *J. Ship Res.* 51(2) pp 174–181
[58] Odegard V 2009 Nonlinear Identification of Ship Autopilot Models *Norwegian University of Science and Technology* 29 pp 100–107
[59] Castro J L 1995 Fuzzy logic controllers are universal approximators *IEEE Transactions on Systems, Man, and Cybernetics* 25 (4) pp 629–635
[60] Do Kh 2011 Global robust and adaptive output feedback dynamic positioning of surface ships *Journal of Marine Science and Application* 10 (3) pp 325–332
[61] Kapitanyuk Yu, Proskurnikov A and Ming Cao Optimal controllers for rudder roll damping with an autopilot in the loop *IFAC-PapersOnLine* 49-23 (2016) 562–567
[62] Maruf A, Kadir R E A, Gamayanti N, Santoso A, Bilfaqih Yu, Sahal M and Hidayat Z L1 adaptive controller for unmanned surface vehicle type monohull LSS01 autopilot system and guidance design *IOP Conf. Series: Earth and Environmental Science* 649 (2019) 012055
[63] Volyanskaya Ya B, Volyanskiy S M and Onishchenko O A 2017 Brushless valve electric drive with minimum equipment excess for autonomous floating vehicle *Electrotechnical Complexes and Systems* 4 pp 26–33
[64] Volyanskaya Ya, Volyanskiy S, Onishchenko O and Nikul S 2018 Analysis of possibilities for improving energy indicators of induction electric motors for propulsion complexes of autonomous floating vehicles *Eastern-European journal of enterprise technologies* (Kharkiv: PC TECHNOLOGY CENTER) 2/8(92) pp 25–32
[65] Volyanskaya Ya, Volyanskiy S, Onishchenko O and Shevchenko V 2019 Research of possibilities to increase the exactness of ship stabilizing on a course *Marine Intellectual Technologies* (*Electronic Materials* vol 3) (St. Petersburg: Research Centre «Marine Intelligent Technologies») 3(45) pp 174–181