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Application of fuzzy controllers in automatic ship motion control systems

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ABSTRACT

Automatic ship heading control is a part of the automatic navigation system. It is charged with the task of maintaining the actual ship's course angle or actual ship's course without human intervention in accordance with the set course or setting parameter and maintaining this condition under the effect of disturbing influences. Thus, the corrective influence on deviations from a course can be rendered by the position of a rudder or controlling influence that leads to the rotary movement of a vessel around a vertical axis that represents a problem, which can be solved with the use of fuzzy logic. In this paper, we propose to consider the estimation of the efficiency of fuzzy controllers in systems of automatic control of ship movement, obtained by analysis of a method of the formalized record of a logic conclusion and structure of the fuzzy controller. The realization of this allows to carry out effective stabilization of a course angle of a vessel taking into account existing restrictions.

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1. INTRODUCTION

The course stabilization system is designed to automatically maintain the vessel's diametric plane in a given direction relative to the compass meridian. The functioning of the main loop of the ship's course stabilization system is known to be characterized by dynamic processes. Nonlinear nonstationary models describe these processes, under conditions of variable perturbations such as wind, waves, current, shoals, cargo-ballast condition, and control actions, in general case [1]–[5]. Technical realization of the tasks of stabilization of modes of such class of control systems relies on the use of a set of different mechanisms: adaptation, application of principles of robustness (roughness), invariance to perturbations, and other processes [6]–[8]. Thus, for an adaptive automatic control system (ACS) with a reference model, the methodology of construction of robust control algorithms for nonstationary objects, using classical quadratic criterion of absolute stability and/or hyperstability criterion, is presented in [9], [10]. Bai *et al*. [11], Huang and Li [12] optimized backstepping design for ship course following control based on actor-critic architecture with input saturation. Systems with reference model (RM) allow a uniform procedure for developing families of robust control algorithms for a variety of nonstationary objects synthesized without applying the hypothesis of quasi-stationarity of dynamic processes. A number of control algorithms with RM do not apply time function inversion procedures. As a consequence, the obtained laws of control loop functioning become similar to the known ones: for control systems with variable structure, for binary systems, and for systems with signal and parametric self-tuning. Depending on the method of setting RM, where RM itself can be present in ACS in the explicit form, representing a real dynamic link, or in the implicit form, as a number of coefficients of the differential equation, the solutions of which have the desired properties of quality indicators of the dynamic process. When synthesizing adaptive and robust ACSs with an explicit reference model, the structural coordination of the explicit reference model (ERM) and the object must be provided by using reduced-order models of the closed loop (object), which dramatically complicates not only the technical implementation but also the adjustment of the control system.

For many applied tasks, the application of classical methods of the theory of robust and adaptive control is not always rational, because it implies a significant complication of the system by rejecting classical structures (for example, the construction of systems with subordinate coordinate control), the transition to control with identification of object variables in real-time by means of state observers. To ensure safe control of the ship's course, the ACS has strict requirements for reliability and dynamic properties that depend on many factors, which require the development of controllers based on the ship model. Application of fuzzy neural network in ship course control to design a course system to ensure the robustness of the course control system. Thus, Contreras [13] studied generating fuzzy singleton controllers to ship course control, Hu *et al*. [14] application of fuzzy neural network to ship course control, design of ship course control based on fuzzy proportional integral differential (PID) algorithm proposed by An *et al.* [15]. Liu [16] conducted a study on ship course keeping using different sliding mode controllers. Morawski *et al*. [17] researched design ship course control system. Rybczak and Rak [18] studied prototyping and simulation environment of ship motion control system. Hao *et al.* [19] applied recurrent neural networks for nonparametric modeling of ship maneuvering motion. Further applications of fuzzy neural networks in ship course control systems were provided in [20]–[22]. Maintaining ship course using different sliding mode controllers and parameter identifiability of ship maneuvering modeling using system identification including the application of Kalman filter [23], [24]. Iterative lead compensation control of nonlinear marine vessels maneuvering models studied in [25], [26]. Application of models and methods that increase the stability of the ship on a given course is a logical way to systematic improvement of the safety of navigation [27]–[31]. Light on the research forms of fuzzy logic approach in education and overview of fuzzy logic and fuzzy systems and concept presented in [32]–[34].

2. METHOD

For the considered ACS containing a "smooth" model of a seagoing ship the ranges of variation of parameters and loads, as a whole, are known and cause deterioration of quality indicators only of dynamic processes. Under such conditions, the problem of ensuring the coarseness of the system is narrower and can be solved without the application of RM and state observers by the formation of nonlinear characteristics of controllers. If we assume that the characteristics of controllers functionally depend on the amplitude and rate of change of the control error, we can proceed to the systems with fuzzy control that were proposed at the end of the last century, where fuzzy controllers (FCs) of Mamdani with symmetric triangular identity functions and single-tone way of phasing and dephasing by finding the center of gravity are universal approximators.

Fuzzy control has certain properties of coarseness, and combining several fuzzy controllers allows to obtain of good dynamic properties of the system, and a small number of FC rules gives improved generalization properties. It should be noted that in order to ensure the compatibility of the equipment, as well as to ensure its competitiveness, the technical implementation of FCs must comply with the standard for programmable microcontrollers. This standard introduces typical, very limited, laws of the description of fuzzy control elements in controller programming languages, fixed by IEC 61131-3. For analog control objects, it is, for example, the function block diagram language. The standard defines the model and functional elements of FC such as fuzzification, defuzzification, producing rules according to the algorithm of sequential operations (aggregation), activation, accumulation, and the commands of the generic language, fuzzy control language, for developing fuzzy control systems are defined.

The fulfillment of the IEC 61131-7 standard drastically limits the very diverse, theoretically possible, solutions to the creation of FC, thus noticeably simplifying the task of technical implementation and interoperability of a particular FC. Note, that FC implementation can be both hardware and software, and microcontrollers (MC) with support of many IEC standardized fuzzy logic commands produced by Siemens, Fuji Electric, Motorola, Intel, Yokogawa, Klockner-Möeller, Rockwell Automation, Allen-Bradley, and other well-known companies. Despite the fact that FC can be successfully implemented on the basis of universal controllers that have a sufficient set of functions (e.g., Texas instruments), very prospective implementation of

FC on the basis of specialized fuzzy integrated circuits (fuzzy chips) and fuzzy processors (fuzzy processors): adaptive logic, 68HCxx, MCS-96, TOGAI-Infra Logic F110, and FUZZY-166. Such chips are easy to integrate into existing control systems and have a low price and are successfully used even in household appliances. According to the standard IEC 61131-7 the functional diagram of FC shown in Figure 1, contains the following nodes: phasing, logic conclusion with rule base, and defuzzification. The following sequence of processing input variables by a fuzzy controller is the most common.

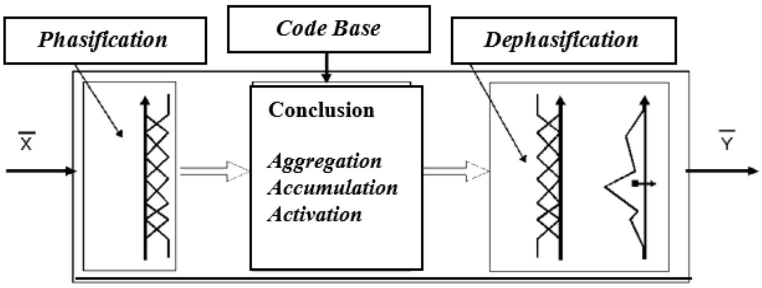

Figure 1. Typical representation of fuzzy controllers

The first phase of phasification is a fuzzy reduction, i.e., their degrees of affiliation are calculated for the clear numerical data. At this stage (conversion of explicit input variables into their fuzzy, linguistic values) the admissible range *D* of input variables changes is divided into qualitative sets-terms (small negative (*NS*), zero (*Z*), and small positive (*PS*)). The degree of membership of variables in the set is determined by the membership functions (MF) of the set $\mu_j(\cdot)$, satisfying for any x_i the condition of consistency: $\sum^j \mu_j(x_i)$=1. For instance, the use of single-type membership functions allows simplifying the mathematical description of the phasing procedure, as illustrated in Figure 2.

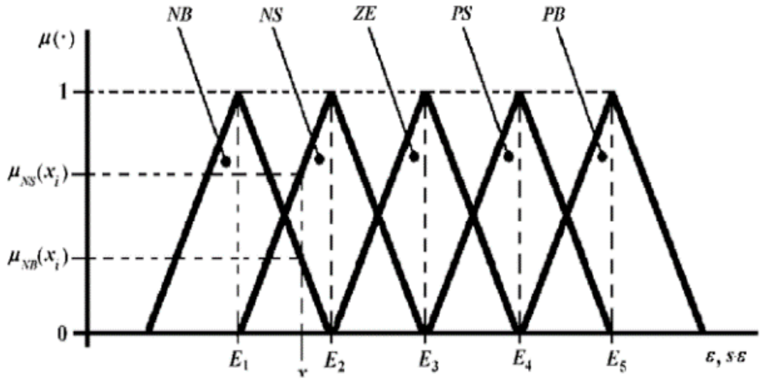

Figure 2. Phasification stage

Phasification is performed for at least two input variables. The variables are transformed into the corresponding logical variables $\bar{x}$ by means of affiliation MFs, and all input variables (terms) $\mu(\bar{x})$ are considered to be phasis-singletons-independent samples. During transformations of logical variables, a logical conclusion is made based on the rules formulated by subject matter experts. A set of fuzzy rules $\bar{A} \Rightarrow \bar{B}$, in general, is written in (1).

$$IF(x_1 \in A_1)AND\ldots(x_j \in A_j)$$
$$AND\ldots(x_n \in A_n)THEN(y \in B_i) \quad (1)$$

Conclusion means obtaining the resulting membership functions for each of the output variables. This block includes a rule base, an inference mechanism, and a set of membership functions for each of the output variables. The realization of transformations (1) requires finding MFs. The simplest case of the representation of logical variables is regulation error x_1=ε and its derivative x_2=s·ε with triangular MFs $\mu_j(\cdot)$. The operation *AND* in (1) corresponds to the intersection of the sets, and the result of applying all the rules corresponds to the operation of combining (aggregating) the sets.

For example, if the *N-rule* is formulated: *Rule N*: *IF* (ε ∈ *NS*) *AND* (*s*·ε ∈ *PS*), *THEN* (*y* ∈ *ZE*). Then MF for the intersection of the two sets *NS* и *PS* is written as $\mu_{\varepsilon \cap s\cdot\varepsilon} = \min(\mu_\varepsilon, \mu_{s\cdot\varepsilon})$. The union as–$\mu_{\varepsilon \cap s\cdot\varepsilon} = \max(\mu_\varepsilon, \mu_{s\cdot\varepsilon})$.

The MFs, for each of the sets included in the fuzzy output variables in rules (1), are obtained as (2),

$$\left.\begin{aligned} \mu_1(\bar{y}) &= min\{\mu_{y1}(\bar{y}), min(\mu_{\varepsilon 1}(\varepsilon), \mu_{s.\varepsilon 1}(s.\varepsilon))\} \\ \mu_j(\bar{y}) &= min\left\{\mu_{yj}(\bar{y}), min\left(\mu_{\varepsilon j}(\varepsilon), \mu_{s.\varepsilon j}(s.\varepsilon)\right)\right\} \end{aligned}\right\} \tag{2}$$

and the rules containing the same consequences and relating 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 (3). The transformation of the result into the output signal (defuzzification) is performed by (4) determining the "center of gravity" $\bar{y}_c$ for $\mu(\bar{y})$.

$$\mu(\bar{y}) = \max\{\mu_1(\bar{y}), \ldots, \mu_j(\bar{y})\} \tag{3}$$

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

Modern fuzzy MCs have full support for variable input/output, unified command systems for all phasing, logic conclusion and defuzzification stages. The main difficulty in applying fuzzy MC lies in developing an effective rule base. The number of rules depends on the number of input variables and the number of values of linguistic variables (fuzzy sets). For example, the implementation of a fuzzy PID controller requires writing a three-dimensional table of rules (the number of rules, with the same number of term-elements on inputs, is defined as the number of linguistic variables in degree of the number of input variables). Writing the table, even with the help of experts, is extremely difficult to formalize for a particular technological control object. This is the reason why FCs can be multi-channel systems containing, for example, *P*, *I* and *D* channels. One of the most universal schemes of *i*-channel connection of FCs is shown in Figure 3.

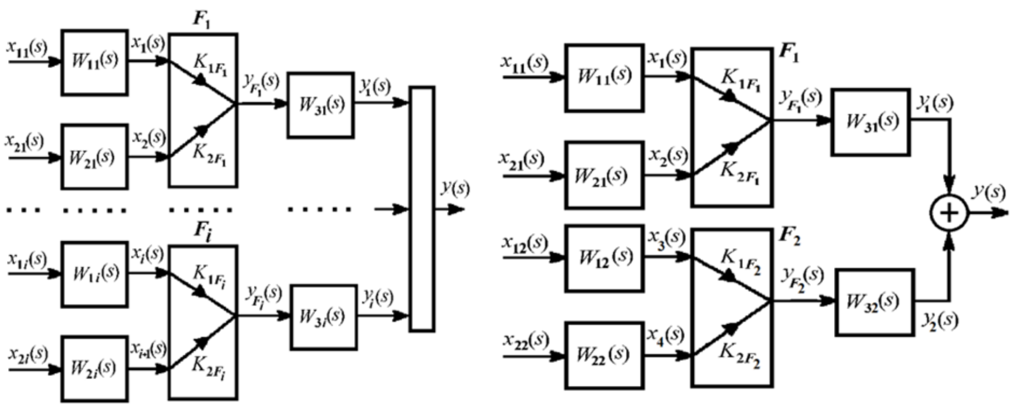

Figure 3. Multi-channel fuzzy controller with two inputs and one output for each channel

Consider a two-channel controller containing two FCs, *F1* and *F2*. Assume that the transfer functions $W_{11}(s)$, $W_{21}(s)$ и $W_{12}(s)$, $W_{22}(s)$ of the input terms $\bar{x}$ are scaling, proportional links; there are two input signals, $x_{11}(s)=x_{12}(s)$ и $x_{21}(s)=x_{22}(s)$, the first being the control error ε(*s*) and the second derivative of $s\cdot\varepsilon(s)\equiv d\varepsilon(\tau)/d\tau$ of the error; the transfer function $W_{31}(s)$ of the first FC performs proportional gain and the second FC $W_{32}(s)$

performs an integration operation with time constant T_I; the nonlinear transfer coefficients K_{1F1}, K_{2F1} and K_{1F2}, K_{2F2} of the fuzzy controllers for each of the terms $x_1(s)$, …, $x_4(s)$ are linearized. Considering that the input terms are divided into 5 and the output term into 7 sets, presenting the set of rules (1) in tabular form for, for example, one of FC's channels-proportional.

Under these conditions, it can be written as (5).

$$\left.\begin{array}{c} W_{11}(s) = k_{P1}; W_{21}(s) = k_{D1}; W_{12}(s) = k_{P2}; W_{22}(s) = k_{D2}; \\ \varepsilon(\tau) = \varepsilon(s) = x_{11}(s) = x_{12}(s); \frac{d\varepsilon(\tau)}{d\tau} = s.\varepsilon(s) = x_{21}(s) = x_{22}(s); \\ K_{1F1} = \frac{\partial F_1(\tau)}{\partial x_1(\tau)}; K_{2F1} = \frac{\partial F_1(\tau)}{\partial x_2(\tau)}; K_{1F2} = \frac{\partial F_2(\tau)}{\partial x_3(\tau)}; K_{2F2} = \frac{\partial F_2(\tau)}{\partial x_4(\tau)}; \\ W_{31}(s) = k_n; W_{32}(s) = \frac{1}{s.T_I} \end{array}\right\} \tag{5}$$

From (5), according to Figure 3, we obtain:

$$\left.\begin{array}{c} y_1(s) = \varepsilon(s).k_{P1}.K_{1F1}.k_P + s.\varepsilon(s).k_{D1}.K_{2F1}.k_P \\ y_2(s) = \varepsilon(s).k_{P2}.K_{1F2}\frac{1}{s.T_I} + \varepsilon(s).k_{D2}.K_{2F2}\frac{1}{T_I} \\ y(s) = y_1(s) + y_2(s) \end{array}\right\} \tag{6}$$

from here the transfer function of the FC:

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

corresponds to the transfer function of an ideal PID controller:

$$W_{FC}(s) = K_n FC + \frac{1}{s\cdot T_{IFC}} + s\cdot T_D FC, \tag{8}$$

where $K_{nFC}=k_{P1}\cdot K_{1F1}\cdot k_P+k_{D2}\cdot K_{2F2}\frac{1}{T_I}$; $T_{I\,FC}=T_I/(k_{P2}\cdot K_{1F2})$; $T_{D\,FC}=k_{D1}\cdot K_{2F1}\cdot k_P$.

3. RESULTS AND DISCUSSION

As the PID controller is universal for almost any process and is one of the most common automatic controllers, its use is reflected in various areas where automatic control is required. This can be from the regulation of the set temperature, maintaining engine speed, all sorts of balancing devices, and of course the system autopilot. The relevant problem is the difference between the current values of the sensor and the setting of the so-called control error, i.e., how far the system is from the set point value. In other words, the larger the error, the larger the control signal will be and the faster the system will bring the controlled variable to the set point value.

We formalize the writing of output rules using the first proposed principle of symmetric writing of logical output: by turning the column of the variable x_2 vertically as compared to the generally accepted representation for the column directions of tables. The rule table thus obtained is monotone, which increases the stability of the closed-loop system and takes into account the fulfillment of the obvious condition $\varepsilon\cdot s\cdot\varepsilon<0$ for the steady-state mode (at $\varepsilon\in ZE$ and $s\cdot\varepsilon\in ZE$, $\varepsilon\to 0$ and $s\cdot\varepsilon\to 0$). It is also obvious that the rules written in the center of the table (inside the circle in Figure 4) provide steady-state and near-steady-state operation, while the remaining rules provide transient modes. Moreover, the exclusion of rules 1, ..., 4 and displacement of MF centers, and in some cases input, terms to the *ZE* region increase the coarseness properties of FC. The mentioned properties of FC with the proposed table of rules and MFs are proved by the results of simulation of the operation of the sea ship's course stabilization system. Since in any technical control system the output signals of sensors are normalized (usually ±10 V), the output signals of control signals and controllers are also normalized to ±10 V. That is why the output signal x_2 (derived from the error ε) also cannot exceed ±10 V. Thus, we can assume that the scaling factors FC $k_{Pi}=k_{Di}=1$, shown in Figure 4.

We determine for the two-input unbiased symmetric triangular terms and the biased output triangular term the coefficients K_{1Fi} and K_{2Fi} of FC as shown in Figure 5. We calculate these coefficients as the ratios of the increments of the $\bar{y}$ FC output signals to the increments of the input signals $\bar{x}$, at small deviations of the terms from the steady-state motion, i.e., near the stabilization mode of the output coordinate of the control system. In the considered FC there are two inputs and one output and for any combination of input phasis-singletons the result of implication will be different from zero only for four "active" rules. According to Figure 4, let us write down the "active" rules.

- For ε=x_{11} and s.ε=x_{21}.

$$\left.\begin{array}{l} IF(x_{11} \in ZE) AND(x_{21} \in ZE), THEN(y \in ZE) \\ IF(x_{11} \in ZE) AND(x_{21} \in PS), THEN(y \in PS) \\ IF(x_{11} \in NS) AND(x_{21} \in ZE), THEN(y \in NS) \\ IF(x_{11} \in NS) AND(x_{21} \in PS), THEN(y \in ZE) \end{array}\right\} \quad (9)$$

- For ε=x_{12} and s·ε=x_{21}

$$\left.\begin{array}{l} IF(x_{11} \in ZE) AND(x_{21} \in ZE), THEN(y \in ZE) \\ IF(x_{11} \in ZE) AND(x_{21} \in PS), THEN(y \in PS) \\ IF(x_{11} \in PS) AND(x_{21} \in ZE), THEN(y \in PS) \\ IF(x_{11} \in PS) AND(x_{21} \in PS), THEN(y \in PB) \end{array}\right\} \quad (10)$$

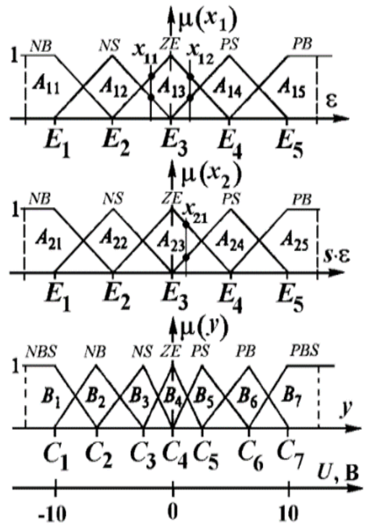

Figure 4. Scaling the FC terms and determining the coefficient K_1F_1

Using expressions to determine the triangular form terms we write:

- For ε=x_{11} and s·ε=x_{21}

$$\left.\begin{array}{c} K_{1F1} = \frac{\partial \Delta y}{\partial \Delta x} \to \infty \frac{E_3 - x_{11}}{E_3 - E_2} \\ \mu(x_{21} \in ZE) = \frac{E_4 - x_{21}}{E_4 - E_3}; \mu(x_{21} \in PS) = \frac{x_{21} - E_3}{E_4 - E_3} \end{array}\right\} \quad (11)$$

- For ε=x_{12} and s·ε=x_{21}

$$\left.\begin{array}{l} \mu(x_{12} \in ZE) = \frac{E_4 - x_{12}}{E_4 - E_3}; \mu(x_{12} \in PS) = \frac{x_{12} - E_3}{E_4 - E_3} \\ \mu(x_{21} \in ZE) = \frac{E_4 - x_{21}}{E_4 - E_3}; \mu(x_{21} \in PS) = \frac{x_{21} - E_3}{E_4 - E_3} \end{array}\right\} \quad (12)$$

The resulting signals are determined using a well-known simplification of (4),

$$y_c = \frac{\sum_{i=2}^{4} \mu_i C_i}{\sum_{i=1}^{4} \mu_i} \quad (13)$$

where μ_i–value of MF, assigned to i^{th} term; C_i center i^{th} output term. Then from (13),

$$y_{c11} = \frac{(x_{11}-E_2)C_4-(x_{11}-E_3)C_5}{2(E_3-E_2)} + \frac{(x_{21}-E_3)C_4-(x_{21}-E_4)C_3}{2(E_4-E_3)}$$
$$y_{c12} = \frac{(x_{12}-E_3)C_5-(x_{12}-E_4)C_4}{2(E_4-E_3)} + \frac{(x_{21}-E_3)C_6-(x_{21}-E_4)C_5}{2(E_4-E_3)} \quad (14)$$

denoting $\Delta y=(y_{c12}-y_{c11})$ and $\Delta x=(x_{12}-x_{11})$, at $x_{21}\to E_3$ we obtain $K_{1F1} = \frac{\partial \Delta y}{\partial \Delta x} \to \infty$.

That is, with infinitely small input signals, the transfer coefficient of FC tends to an infinitely large value, thereby, near the stabilization point of the output variable, gives the control system astatic properties. This reduces to zero the steady-state control or tracking errors that arise under the influence of controlling or disturbing influences on a given system as shown in Figure 5.

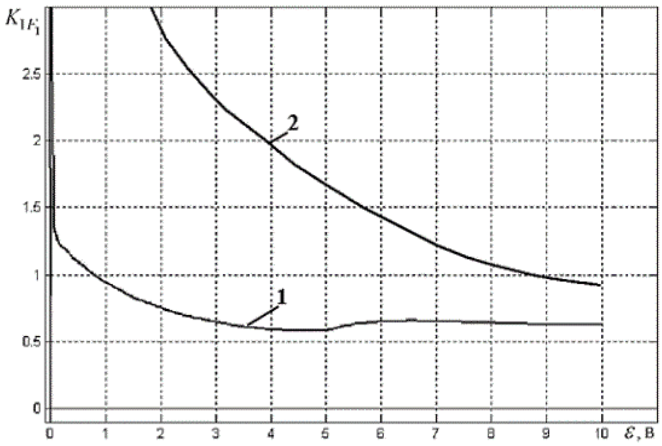

Figure 5. Dependencies of the error transfer coefficient of the fuzzy controller at: 1–$s\cdot\varepsilon \to E_3$; 2–$s\cdot\varepsilon \to E_5$

Using a similar approach ((9) to (14) for x_{12} and x_{21}) when normalizing to ±10 V input and output signals, we can calculate the K_{1F1} FC gain for the whole range of $E_1 \ldots E_5$ variations of input signals Figure 6. Obviously, if the rule table and the output terms are symmetric, the input terms are symmetric and their number is equal, then for this case $K_{1F1} = K_{1F2}$. Consequently, if we install in each of the channels of the two-channel, implementing the adaptive properties of the fuzzy PID controller Figures 3 and 4, two absolutely identical FC with the same scaling factors k_{Pi} и k_{Di}, then the resulting structural scheme can be simplified by eliminating FC in one of the channels.

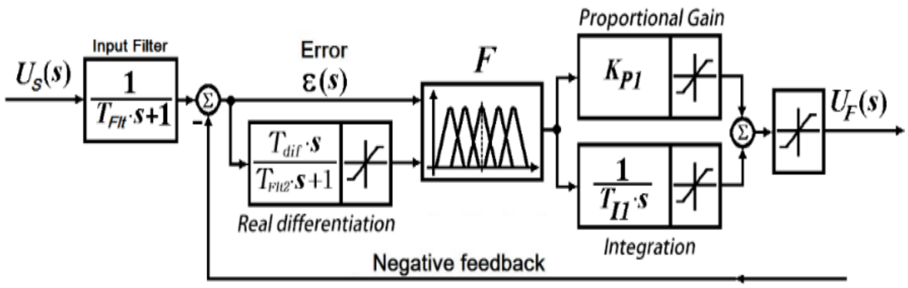

Figure 6. Block diagram of a fuzzy PID controller

Taking into account the scaling of signals and their limitation, such a scheme is shown in Figure 6. The response to a single spike (at T_{Flt}=0; T_{D1}=1 sec; T_{I1}=0,04 sec; K_{P1}=5, and the diffraction operation is real, with a time constant of 0.001 sec), obtained from the simulation and shown in Figure 7, confirms the PID properties of the FC with output signal limitation at ±10 V. The results of comparing the response of the PID controller and the fuzzy controller confirm the coincidence of the properties of the two regulators in nominal mode. In addition, the fuzzy properties provide robustness of the system.

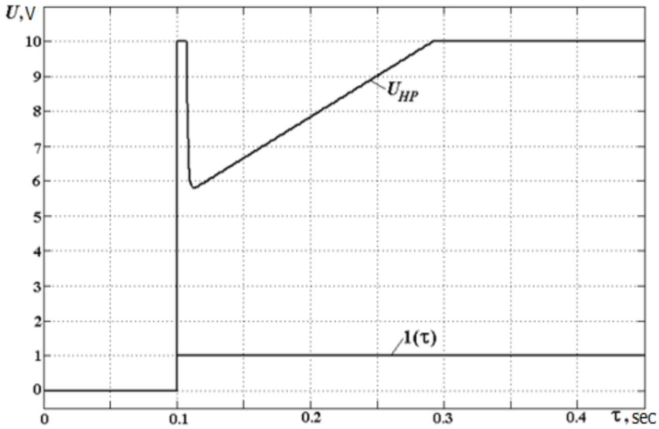

Figure 7. Fuzzy PID controller response to a single spike

Consequently, using the similarity of (7) and (8), it is possible to abandon the method of FC tuning by "expert selection" of its parameters, taking as a basis the PID controller parameters calculated for nominal operating conditions, for example, providing the "technical" optimum. With such a solution, the recorded rules in Figure 4 will give the FC properties of coarseness, and the possibility of the formation of nonlinear properties will be carried out by shifting the center C_i of the output terms. This points to the fact that installation of fuzzy controllers with similar rule tables leads to the almost complete exclusion of oscillations in the system and, despite the properties of the controlled object-a ship varying from the operating mode to a high quality of stabilization modes, irrespective of the value of the course angle set, for stabilization purpose.

4. CONCLUSION

An application of two-channel fuzzy controllers, which implement in nominal mode the properties of PID-controllers with enhanced coarseness properties using a limited number of fuzzy rules is proposed in this study for the stabilization loop of the course angle of the seagoing ship. A formalized method of logical output record and structure of fuzzy controller was proposed firstly, the realization of which allowed to effectively stabilize the heading angle taking into account the existing limitation. Analysis of graphs confirms the nonlinear properties of the controller. Increasing the coarseness properties can be achieved by reducing the number of rules with the system near the steady-state modes by shifting the centers. The research proposes combining several fuzzy controllers with enhanced coarseness properties into a batch (parallel) fuzzy controllers by applying a limited number of rules in them, in particular a combined one, with a "fuzzy parallel+traditional" type structure, for which the main perturbations from the control object are compensated by the fuzzy controllers as a universal approximator. According to the results of the model studies, it was established that subject type of fuzzy controllers provides both asymptotic stability of the system as a whole and robustness of the system from the limited range of changes in the parameters and perturbations of the control object.

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