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RESEARCH ARTICLE

Analysis and synthesis of intelligent automatic control systems with type-1 fuzzy regulator

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Abstract

Objectives. The active development of intelligent automatic control systems, which is associated with increasing requirements to the quality and accuracy of control systems of modern technical systems, requires the development of new approaches to their analysis and synthesis. A promising class of intelligent control devices is based on regulators that use fuzzy-logic inference technology. The purpose of this work is to develop a method for the complex synthesis of type-1 fuzzy regulator parameters on the basis of the Yakubovich circle criterion.

Methods. The proposed methodology is based on a consideration of fuzzy regulators in terms of the corresponding nonlinear transformation that support the use of methods derived from the theory of nonlinear automatic control systems. Analogs of the degrees of stability and oscillation are used as quality indicators. The synthesis of the parameters of the nonlinear transformation can be reduced to determining sufficient regions of absolute stability of the system with the shifted and extended Nyquist plot obtained using the Yakubovich circle stability criterion.

Results. In accordance with the theory of fuzzy sets and algorithms of fuzzy logical inference described by Takagi–Sugeno, the possibility of one-to-one correspondence of the nonlinear transformation and the parameters of an appropriately arranged knowledge base of the fuzzy controller is shown. A procedure proposed for synthesizing the parameters of the type-1 fuzzy regulator is aimed at ensuring complex requirements for the quality of the control system according to the degree of stability, the degree of oscillation, and steady-state mode accuracy. The effectiveness of the proposed technique, which guarantees the absolute stability not only of the equilibrium position but also of the processes, is confirmed by the results of model experiments.

Conclusions. The paper proposes a convenient engineering technique for determining the parameters of an intelligent controller constructed using fuzzy logic inference technology based on methods informed by automatic control theory. The convenience of using such indirect quality indicators as the degree of stability, the degree of oscillation, and accuracy in steady-state mode, is demonstrated. These indicators are explicable for developers of applied control systems.

Keywords: intelligent control system, fuzzy logic inference, fuzzy controller, Takagi–Sugeno model, absolute stability of processes

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НАУЧНАЯ СТАТЬЯ

Анализ и синтез интеллектуальных систем автоматического управления с нечетким регулятором I рода

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Резюме

Цели. Активное развитие интеллектуальных систем автоматического управления, связанное с повышением требований к качеству и точности систем управления современных технических систем, требует разработки новых подходов к их анализу и синтезу. Одним из перспективных классов интеллектуальных управляющих устройств выступают регуляторы, построенные на базе технологии нечеткого логического вывода. Целью настоящей работы является разработка методики комплексного синтеза параметров нечеткого регулятора I рода на основе кругового критерия Якубовича.

Методы. В основу предлагаемой методики положено рассмотрение нечеткого регулятора с позиции соответствующего нелинейного преобразования, что позволяет использовать методы теории нелинейных систем автоматического управления. В качестве показателей качества в работе используются аналоги понятий «степень устойчивости» и «степень колебательности». Синтез параметров нелинейного преобразования сводится к определению достаточных областей абсолютной устойчивости системы со смещенной и расширенной амплитудно-фазовыми частотными характеристиками, полученных с помощью кругового критерия устойчивости Якубовича.

Результаты. В соответствии с теорией нечетких множеств и алгоритмом нечеткого логического вывода Такаги – Сугено показана возможность взаимно-однозначного соответствия нелинейного преобразования и параметров базы знаний нечеткого регулятора при соответствующей организации последней. В работе предложена процедура синтеза параметров нечеткого регулятора I рода, нацеленная на обеспечение комплексных требований к качеству системы управления по «степени устойчивости», «степени колебательности» и точности в установившемся режиме. Предложенная методика также гарантирует абсолютную устойчивость не только положения равновесия, но и процессов, а ее эффективность подтверждена результатами модельных экспериментов.

Выводы. В работе предложена удобная инженерная методика настройки параметров интеллектуального регулятора, построенная по технологии нечеткого логического вывода на основе методов теории автоматического управления. Показано удобство применения таких косвенных показателей качества, как «степень устойчивости», «степень колебательности» и точность в установившемся режиме.

Ключевые слова: интеллектуальная система управления, нечеткий логический вывод, нечеткий регулятор, модель Такаги – Сугено, абсолютная устойчивость процессов

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INTRODUCTION

Intelligent technologies have been increasingly applied in various fields of activity over the last two or three decades. One such field is automatic control systems (ACS) [1], for which a new generation of controllers based on intelligent technologies (expert systems, neural-like networks, associative memory or fuzzy logic) is being developed. These intelligent controllers not only provide high quality ACS performance, but are also capable of adaptation to various uncertainties affecting the system.

Among these intellectual technologies, fuzzy inference or fuzzy logic is the most widely used for both objective and subjective reasons [2–4]. In robotics, fuzzy logic is already commonly applied in the control systems of autonomous and semi-automatic robots of various types, in the control systems of complex technological equipment, as well as at all hierarchical levels of intelligent control systems (strategic, tactical, and executive). This is largely due to the possibility of using a fuzzy inference system (FIS) to construct control models even for complex objects at the level of logical-linguistic reasoning.

However, this novel formalism is not entirely compatible with current automatic control theory (ACT). In particular, a serious problem has arisen in connection with the creation of new approaches to solving the stability and quality evaluation problems pertaining to a new class of automatic control systems. This problem has been solved quite actively in the last two decades. A comprehensive generalization of the work is given in the monograph by Pegat [5]. The concept proposed at the beginning of the present century in the RTU MIREA by Makarov et al. has turned out to be very promising [1]. Summarizing the long-term research experience in the field of fuzzy ACS taking into account the results of the studies presented in [1–6], it can be stated that:

1. Fuzzy inference allows the synthesis of logical-linguistic control models for complex objects.
2. Despite the apparent complexity of the fuzzy inference formalism, it has been established that the fuzzy regulators (FR) based on this technology are

essentially nonlinear. This means that they implement a nonlinear transformation, whose parameters can change slightly when the fuzzy inference technology is modified (Mamdani, Sugeno, etc.).

3. The nature of the nonlinear transformation in FR unambiguously determines the parameters of the input logical-linguistic variables.

The representation of FR as a nonlinear ACS element provides a broad perspective for incorporating traditional approaches to nonlinear systems adopted in ACT and modified taking the specific nature of nonlinear transformations in the study of intelligent ACS into account.

SPECIFIC FEATURES OF ACS ANALYSIS AND SYNTHESIS WITH FR

We consider a fuzzy logic system having an input (E) and an output (U) linguistic variable with reasoning domains on $X_E \subseteq \mathbb{R}$ and $Y_U \subseteq \mathbb{R}$, for which the corresponding term sets T_E and T_U are given. Each value of a linguistic variable from the underlying term set is given by the normal fuzzy sets $A_i^E = \{(\mu_A(e), e) | e \in X_E\}$ and $A_i^U = \{(\mu_A(u), u) | u \in X_U\}$. Fuzzy inference models currently in active use include the Mamdani, Larsen, Takagi–Sugeno, and Tsukamoto models, which have their relative advantages and disadvantages [7]; regardless of the model type, the resulting fuzzy transformation can be represented as a certain nonlinear mapping $f: X_E \rightarrow Y_U$.

Nevertheless, some general principles of FR design have been formulated by most developers of fuzzy control systems, namely:

1. The number of fuzzy sets in the underlying term sets: 5–7.
2. The term set should contain at least one fuzzy set defined by the membership functions (MF) of classes L and γ to limit the control value. This is related to the ACS physical characteristics.
3. The symmetry of the MF position with respect to the central MF to ensure control symmetry when the system state deviates from equilibrium.

The division of FR into type 1 and type 2 proposed in [1] depends on the processing method of the input

variables. This paper considers the ACS using the most popular type-1 FR based on the Takagi–Sugeno fuzzy inference model to be the most promising. This is primarily due to the lightweight defuzzification procedure representing the weighted mean calculation, which requires significantly less hardware resources and controller processor time compared to other methods. Additionally, the mapping implemented by the fuzzy model involving a piecewise linear function, which is dependent on the appropriate arrangement of the knowledge base, greatly simplifies both the analysis and synthesis of fuzzy ACS. The latter factor will be discussed in detail.

An excerpt of the fuzzy system is shown in Fig. 1, where two fuzzy sets A_{i-1}^E and A_i^E are defined by the class i MF triples $\{a_{i-1}, b_{i-1}, c_{i-1}\}$ and $\{a_i, b_i, c_i\}$, respectively, on some reasoning interval.

We will obtain the expression for the mapping f in the range of the input actions $[b_{i-1}, b_i]$. Let the rule base contain two condition-action rules having the following form:

1. If E is A_{i-1}^E then $U = u_{i-1}^*$,
 2. If E is A_i^E then $U = u_i^*$,
- where $u_{i-1}^* \equiv \text{const}$, $u_i^* \equiv \text{const}$.

In this case, the degree values of the linguistic variable E belonging to the fuzzy sets A_{i-1}^E and A_i^E during fuzzification are defined as follows:

$$\mu_{i-1}(e) = \frac{c_{i-1} - e}{c_{i-1} - b_{i-1}}, \quad \mu_i(e) = \frac{e - a_i}{b_i - a_i}. \quad (1)$$

According to the Takagi–Sugeno fuzzy inference procedure and the adopted constraints on MF parameter values, the output variable is defined as follows:

$$\begin{aligned} u_i(e) &= \frac{\mu_{i-1}u_{i-1}^* + \mu_i u_i^*}{\mu_{i-1} + \mu_i} = \\ &= \left(\frac{b_i - e}{b_i - b_{i-1}} u_{i-1}^* + \frac{e - b_{i-1}}{b_i - b_{i-1}} u_i^* \right) \div \left(\frac{b_i - e}{b_i - b_{i-1}} + \frac{e - b_{i-1}}{b_i - b_{i-1}} \right) = \\ &= \frac{u_i^* - u_{i-1}^*}{b_i - b_{i-1}} e + \frac{b_i u_{i-1}^* - b_{i-1} u_i^*}{b_i - b_{i-1}}. \end{aligned} \quad (2)$$

Thus, the mapping f is a linear function on the interval $[b_{i-1}, b_i]$, whose definition area is given by the location of the vertices of adjacent MFs, while its range is given by the value of the rule base conclusions.

Using the results of the above analysis, the fuzzy ACS based on the above principles can be represented as a nonlinear system, whose FR static characteristic is piecewise linear (Fig. 2). Thus, it is possible to carry out a comprehensive analysis of the dynamics of the fuzzy ACS according to the theory of nonlinear systems with regard to the nonlinear transformation characteristics.

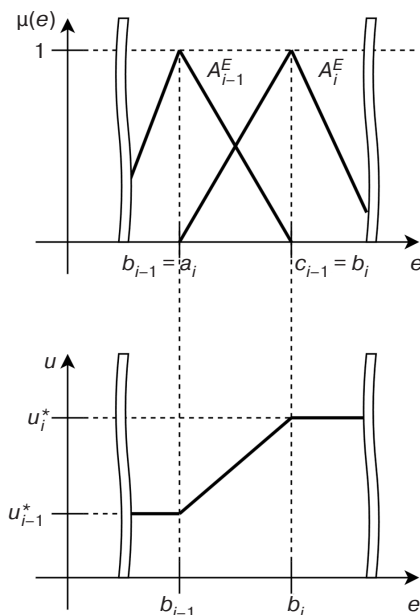


Fig. 1. Relationship between the MF parameters and the type of the nonlinear mapping

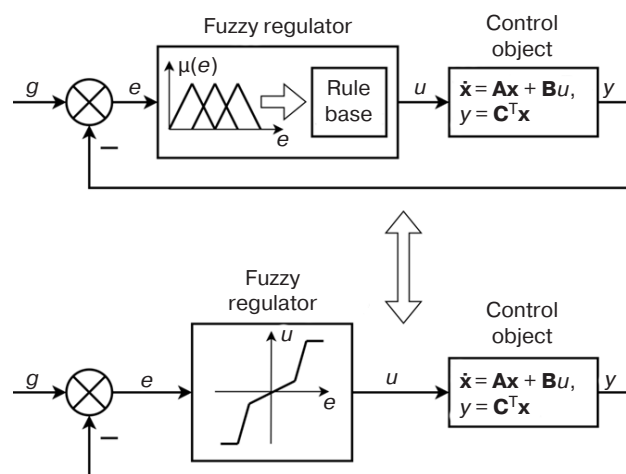


Fig. 2. Conversion of an intelligent ACS with FR into a nonlinear ACS. Here, g is the master control; u is the control action; y is the control object output; $\mathbf{x}$ is the state vector; $\mathbf{A}$ is the system matrix; $\mathbf{B}$ is the control matrix; $\mathbf{C}$ is the output matrix

So far, several approaches have been developed for analyzing the stability of systems with FR. As noted in [5], despite the intensive development of new methods, the second Lyapunov method [8, 9] and the absolute stability criterion [10, 11] continue to be the most widely used. For single-input-single-output (SISO) systems, the Popov criterion and the circular criterion are recommended. For multiple-input-multiple-output (MIMO) systems, the most appropriate methods are those based on the hyperstability criterion due to providing a rigorous mathematical basis for stability evaluation.

The lack of convenient engineering methods to evaluate the qualitative parameters of these systems, such

as speed and overshoot, is evident in a sufficient number of studies on the stability of fuzzy systems. This approach to the problem is more constructive due to the stability problem being automatically solved by achieving the required level of ACS quality. However, as shown by the analysis of existing studies, this problem has been insufficiently studied and remains to be worked out.

In addition to analytical methods for studying fuzzy ACS, methods based on numerical optimization algorithms including genetic algorithms [12, 13], methods related to particle swarm behavior [13, 14], gradient descent [15, 16], and others, are currently gaining wide popularity. Although these methods are powerful and capable of automatically determining the FR parameters, their use in practical engineering is exacerbated by a number of factors. Firstly, in order to use these techniques effectively, the quality function should be precisely defined, which can be a challenge. In addition, the algorithms do not provide any guidance for further adjustment of the FR parameters following their calculation on the basis of the quality criteria.

In view of the obvious potential of fuzzy systems and the relevance of FR implementation in a wide range of control systems for industrial and special purposes, the above analysis demonstrates a need to create new approaches to the study of the dynamics of such systems based on the traditional methods adopted in ACT. Based on the proposed concept, in which fuzzy ACS is considered as a nonlinear system, a suitable platform can be created for this purpose.

It is convenient to take analogs of known quality indicators for linear ACS as initial quality indicators, in particular, the stability degree as an indicator of transient damping rate and the oscillation degree as an indicator of oscillation damping. By considering FR in terms of its static characteristics, it is possible to adapt known methods for analyzing and synthesizing nonlinear ACS (in particular the Yakubovich circle stability criterion). In [17], it is shown that this criterion can be applied to the shifted amplitude-phase-frequency response (APFR) of the linear part to determine the sectional constraints on the nonlinear transformation that guarantee a certain degree of stability for the fuzzy ACS, as well as the absolute stability of the equilibrium position and processes. In this respect, an extension of this method to include oscillation degree and fuzzy ACS accuracy requirements seems promising.

ALGORITHM FOR SETTING I TYPE FR PARAMETERS BASED ON INDIRECT PERFORMANCE INDICATORS

The fuzzy system model, analogous to describing nonlinear systems adopted in ACT, can be represented as follows:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}u, \\ u &= f(y), \\ y &= \mathbf{C}^T \mathbf{x},\end{aligned}\tag{3}$$

where $\mathbf{x} \in \mathbb{R}^n$, $u \in \mathbb{R}^1$, $f(y)$ is a scalar function which is the FR static input-output characteristic and belongs to the class $(K_1; K_2)$ and thus satisfies the equation [2], as follows:

$$K_1 \leq \frac{df(y)}{dy} \leq K_2.\tag{4}$$

Here the task consists in synthesizing the appropriate FR knowledge base for providing the absolute process stability in fuzzy ACS and the qualitative characteristics of the transient process such as the degree of stability, the degree of oscillation, and accuracy.

For further study, it would be convenient to use the shifted $\bar{W}(j\omega - \eta)$ and extended $\hat{W}(j\omega - m\omega)$ APFR of the linear part, where $W(j\omega) = \mathbf{C}^T(j\omega\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$, η is the analog of the stability degree and m is the analog of the oscillation degree. The family of shifted ($\eta_1 > \eta_0 > 0$) and extended ($m_1 > m_0 > 0$) APFRs for 3rd order linear parts are shown in Figs. 3a and 3b, respectively. The characteristic change in the shifted APFR of the linear part at $\eta = \eta_0$ is due to the transition of one of the poles $W(s)$ to the right complex half-plane.

Let the fuzzy control system be required to provide a fast performance not exceeding the decay time of the exponent $e^{-n_0 t}$, with n_0 chosen such that the degree of irregularity (r) of the shifted linear part $\bar{W}(j\omega - \eta)$ is equal to one.

Using the modification of the circle criterion proposed in [17], the following sufficient condition can be formulated: A fuzzy system, which is absolutely stable in class $(K_1^S; K_2^S)$, has a degree of stability not less than $\bar{\eta}$ provided that the shifted APFR for the linear part of $\bar{W}(j\omega - \eta)$ covers the circle with the center on the real axis at point $-\frac{1}{2}\left(\frac{1}{K_1^S} + \frac{1}{K_2^S}\right)$, passing through points $-\frac{1}{K_1^S}$ and $-\frac{1}{K_2^S}$, which also belong to the real axis, r times.

The extended AFC should be outside the above circle to ensure the required degree of oscillation m . Further, if the required degree of oscillation is provided in section $(K_1^O; K_2^O)$, then both quality requirements are met in section $\{\max(K_1^O; K_1^S); \min(K_2^O; K_2^S)\}$, given the results obtained based on the specified stability. Thus, it is possible to determine the parameters K_1 and K_2

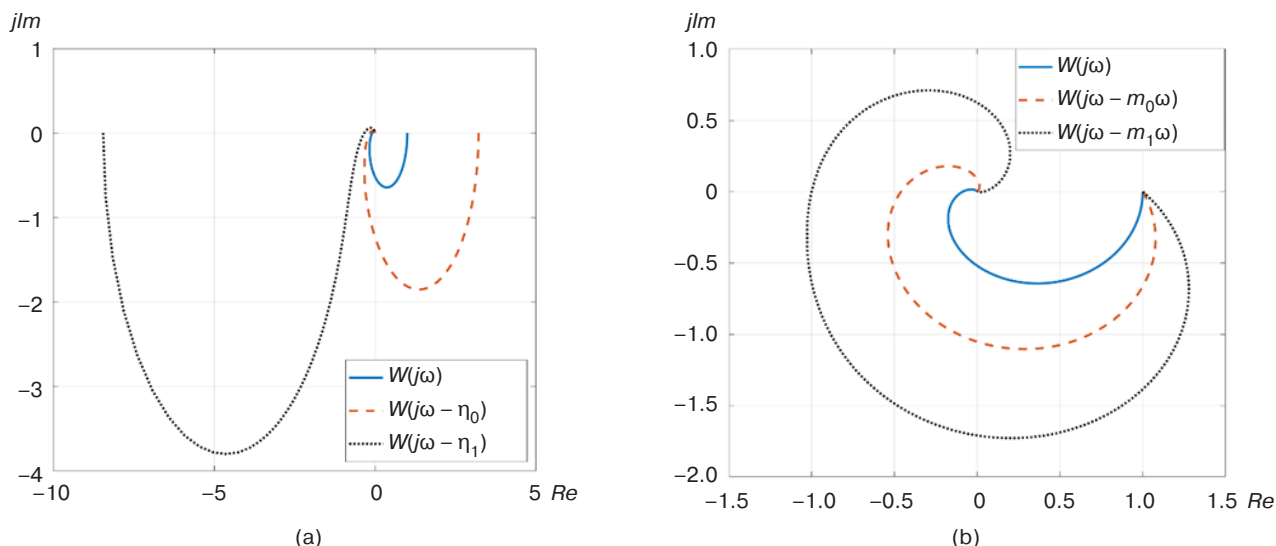


Рис. 3. Family of shifted (a) and extended (b) APFRs of the linear part

of the nonlinear transformation and the corresponding parameters of the FR settings by considering the fuzzy ACS as nonlinear and applying the Yakubovich circle criterion.

Finally, we consider the problem of ensuring fuzzy ACS accuracy. Since the stationary control error of the system is determined by the part of the static characteristic close to the equilibrium, the choice of the gain factor K_1^a is determined by the requirement of the desired accuracy in the whole range of disturbances f . It is shown in [18] that for static linear parts, the stationary error in the range

of disturbances $f \leq \frac{b_1(1 + K_1^a K_{lp})}{K_{lp}}$ is defined as follows:

$$e_{\text{stnr}} = \frac{f K_{lp}}{1 + K_{lp} K_1^a}, \quad (6)$$

where b_1 is the right boundary of the static characteristic section with the gain factor K_1^a , while $K_{lp} = \lim_{\omega \rightarrow 0} W(j\omega)$.

It follows from (6) that if the maximum disturbance value $f_M = \sup(f)$ is known and the permissible control error value e_p is set, the required gain factor K_1^a and the section boundary b_1 are defined as follows:

$$K_1^a = \frac{f_M K_{lp} - e_p}{K_{lp} e_p}, \quad (7)$$

$$b_1 \geq \frac{f_M K_{lp}}{1 + K_{lp} K_1^a}. \quad (8)$$

Thus, the condition of ensuring the required quality indicators of transients and steady-state error is met in the section $(\max\{\max\{K_1^O, K_1^S\}, K_1^a\}; \min\{K_2^O, K_2^S\})$ that ensures the absolute stability of the fuzzy ACS.

We consider an example of the synthesis of the I type FR parameters for the problem of stabilizing the fuzzy ACS equilibrium with a linear part of the 3rd order with a frequency response $W(j\omega)$. In accordance with the methodology discussed above, the necessary constructions are shown in Fig. 4. From these it follows that:

- the required value η_0 is ensured if the FR characteristic is in section (0.6; 2.5);
- the required value m_0 is provided in section (0.05; 6.1).

If the steady-state error requirement and (7) are additionally taken into account, the final desired section is as shown in Fig. 4b. The transient $x(t)$ in fuzzy ACS where FR is typed has a synthesized nonlinear characteristic as shown in Fig. 4c.

Based on the obtained FR nonlinear transformation and the above recommendations for the structure of the knowledge base, the appropriate content can be easily constructed:

- since the synthesized nonlinear transformation has four points of gain factor variation, the term set T_E for the linguistic error variable E will contain five fuzzy sets $T_E = \{A_0, A_1, A_2, A_3, A_4\}$;
- the MFs specifying fuzzy sets A_0 and A_4 belong to classes L and γ respectively (due to the output constraint);
- the remaining MFs belong to class t .

As explained above, the definition area of the i th piecewise linear section of the regulator static characteristic depends on the mutual position of the adjacent MFs. The range depends on the value of the rule base conclusions from the rule base. Running through the entire definition area of the nonlinear characteristic (Fig. 4b) and taking into account its symmetry with respect to the origin of the coordinates, the MF parameters (Fig. 5) can be easily determined

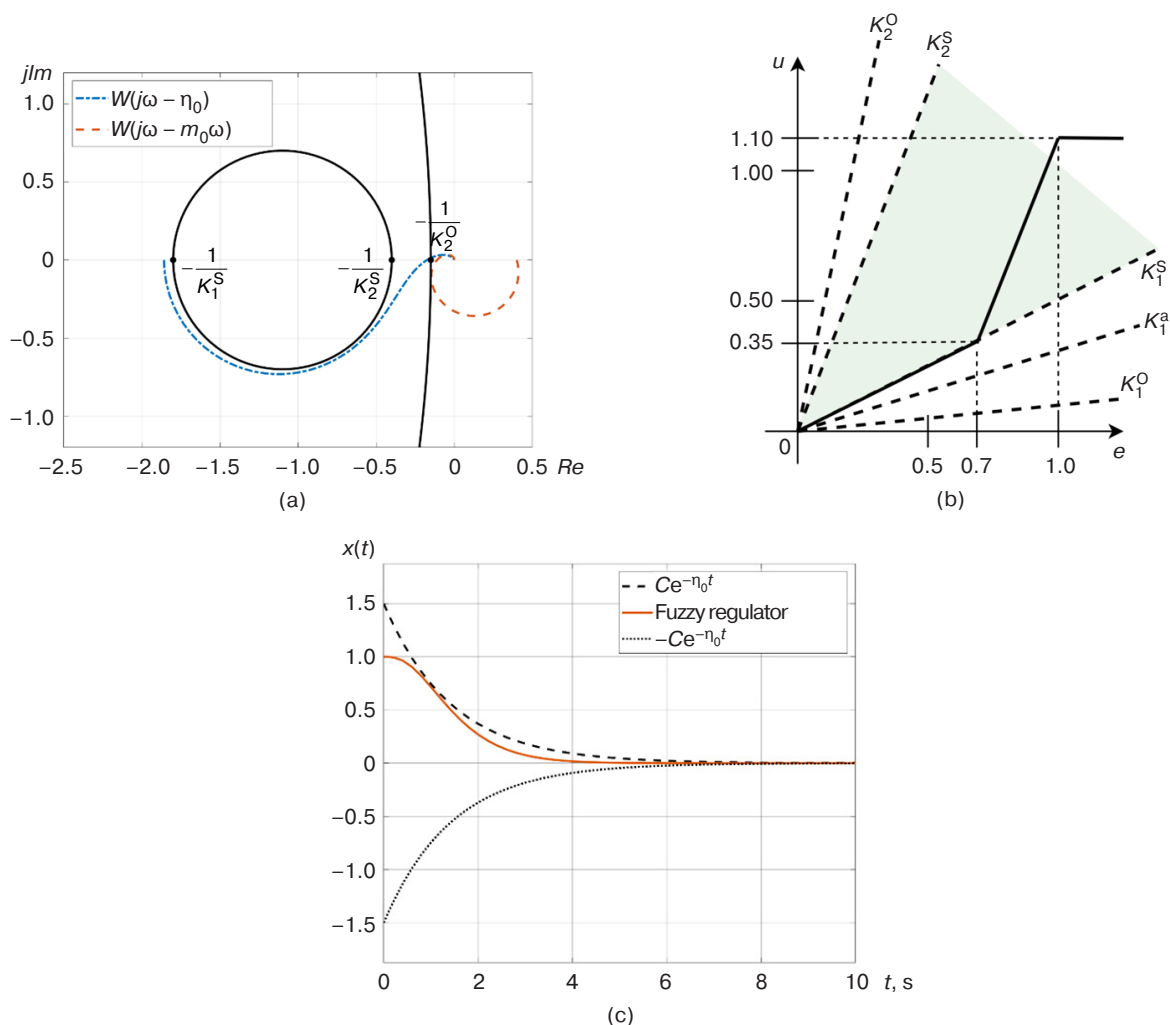


Fig. 4. Yakubovich circular criterion (a), sections of absolute stability with nonlinear characteristic (b), and transient in ACS (c)

for the input variable, as well as the MF values for the output variable embedded in the rule base:

- IF E is A_0 , THEN $u = 1.1$;
- IF E is A_1 , THEN $u = 0.35$;
- IF E is A_2 , THEN $u = 0$;
- IF E is A_3 , THEN $u = -0.35$;
- IF E is A_4 , THEN $u = -1.1$.

CONCLUSIONS

The present work develops the concept proposed by Makarov, according to which the fuzzy Zadeh transformation implemented in the circuit of type-1 FR ACS is in fact a nonlinear transformation. However, it becomes piecewise linear when the Sugeno model is used. For such a fuzzy system that uses methods from the theory of nonlinear control systems, the problem of dynamics research is solved in a form suitable for an engineer-developer. A methodology is proposed, which not only provides a definition of the ensured stability area, but can also be used to provide the required quality indices of the control process.

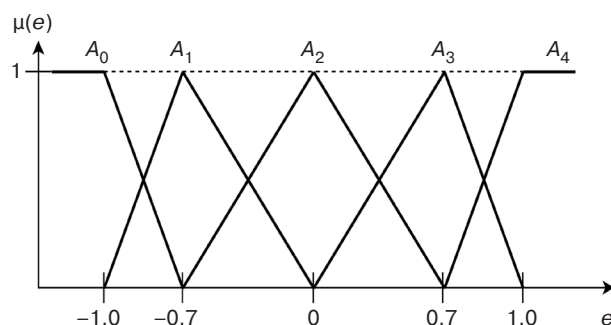


Fig. 5. Arrangement of the MF functions

Obviously, the results will also be valid when Mamdani, Larsen, and Tsukamoto fuzzy inference models are used in control systems: since the nonlinear transformations corresponding to these models are smooth, they can be approximated by piecewise linear sections. Thus, the solution of the problem can be reduced to the proposed method. In this case, the linear approximation section at the origin (having a small slope) is chosen based on the

required steady-state error. Meanwhile, the slope of the steep section is selected based on the quality requirements according to the Yakubovich criterion. This approach can be used to solve analysis and

synthesis problems of fuzzy ACS having a type-1 regulator.

Authors' contribution. All authors equally contributed to the research work.

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