UDC 681.51:621.452.3(045)
DOI:10.18372/1990-5548.58.13510

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FUZZY AUTOMATIC CONTROL SYSTEM SYNTHESIS OF THE PROPELLER FAN THE AVIATION GAS TURBINE ENGINE

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Abstract*—The article deals with the method of automatic control systems synthesis of with a fuzzy controller, which is considered as a separate subsystem within the general control system. Due to the use of the harmonic linearization method, the research of the electronic control system according to the given index of oscillation has been carried out and the fuzzy control system of the aviation engine fan propeller has been designed. Through the simulation, the dependences of the quality the transient process on the parameters of the membership functions for closed systems with fuzzy PI- and PD-regulators were revealed; detected dependencies can be used to form the base rules expert system to configure the regulator from the condition of fulfilling the specified quality criteria.*

Index Term—Automatic control system; aviation gas turbine engine; fuzzy regulator; propeller fan; harmonic linearization.

I. INTRODUCTION

Analysis of the development trends of aviation gas turbine engines (GTE) and their control systems showed [3], [9] that the number of functions performed by automatic control systems (ACS) is determined by the following factors:

- further complication of the engine design and, therefore, the creation of intelligent ACS that change their structure and parameters in a wide range to ensure the most efficient (under given flight conditions) operating mode [3], [7];
- increasing requirements for the quality of control processes, resource, economy, the need for transition to operation on the technical condition [9], [10];
- integration of the ACS GTE into the general automatic flight control system of an aircraft.

Today, to significantly improve the parameters of the ACS for aviation GTE, regulators using the fuzzy logic algorithms are increasingly being used [2], [3], [7], [9], [10]. Fuzzy control will be understood as a control strategy based on empirically acquired knowledge of the object functioning and presented in linguistic form of a certain set of rules [4], [5]. The implementation of fuzzy control algorithms is fundamentally different from the classical ("hard") algorithms that are based on the concept of feedback and reproduce a given functional dependence or differential equation. These functions are connected with a qualitative assessment of the behavior of the system, analysis of the current variable situation and the choice of the most suitable for a given situation control of the GTE. This concept was called forward control concept [1].

II. PROBLEM STATEMENT

Automatic control systems of GTE with fuzzy regulators are nonlinear systems in which stable self-sustained vibrations are possible. Today, when designing such systems, the issues of stability analysis and the quality process of control are not fully resolved due to the complexity of the analytical description of fuzzy systems. By the way, there are researches of eminent scientists in the area of adaptive fuzzy systems S. V. Duplick, L. X. Wang, M. Kratmuller, V. M. Sineglazov, E. Cox, N. R. Yusupbekov, Y. Li, J. Aguilar, B. Novakovic by international companies Securaplane technologies, Boeing, Dryden Flight Research Center NASA, Honewell according to the standards of EUROCAE [1]–[3] Radio Technical Commission for Aeronautics, Eurocontrol, ICAO, EASA and many others.

Therefore, in the field of designing the adaptive control system based on fuzzy logic for turbo propeller fan engine D-27 it is important to regulate rotation speed and thrust of the engine (for reducing the periodic oscillations in nonlinear systems) by setting the value of the regulation error $\varepsilon(t)$ and its derivative $\dot{\varepsilon}(t)$ with the linguistic variables $L_i = \{NL, Z, PL\}$ and fuzzy rules. For solving these problem the harmonic method linearization, that satisfy the Golfarb criterion, is proposed[4].

So, the aim of these research – development the techniques for the synthesis of control systems with a fuzzy regulator as a separate subsystem based on the harmonic method linearization and design on its basis a fuzzy ACS of the aviation propeller fan gas turbine engine.

III. Harmonic Linearization Method

For the use the harmonic linearization method, can be considered a fuzzy controller as a single non-linear element. The block diagram of the ACS of a gas turbine engine with a fuzzy PD controller is shown at the Fig. 1.

Fuzzy PD-controller will be considered as a separate system of a fuzzy automatic control system.

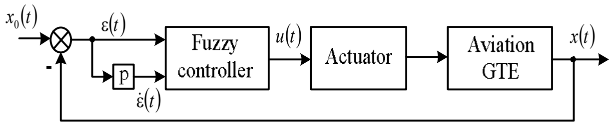

Fig. 1. The block diagram of the ACS of a gas turbine engine with a fuzzy PD controller

Then the block diagram of ACS the GTE with a fuzzy PD-controller can be represented as a series connection of a nonlinear element of the form $u(t)=F[\varepsilon(t),\dot{\varepsilon}(t)]$ and the linear part, which allows using the harmonic linearization method [4].

For linearize the fuzzy controller, a harmonic signal $x(t)=a\sin\varphi$ is applied to its input, where $\varphi=\omega t$. Then $\dot{x}(t)=a\omega\cos\varphi$. The output signal $u(t)=F(a\sin\varphi, a\omega\cos\varphi)$ of fuzzy controller will be periodic, but not harmonic. After decomposition the output signal into a Fourier series and set simplifying assumptions about the absence of a constant component and the fact that the linear part has the properties of a low-pass filter. Then the approximate expression of the output signal of a fuzzy controller is [7].

$$u(t)=q(a,\omega)a\sin\varphi+q'(a,\omega)a\cos\varphi. \quad (1)$$

The same output signal can be obtained if a harmonious signal $x(t)=a\sin\varphi$ is fed to the input of a linear element with the transfer function [8]

$$W_{FC}(a,p)=q(a,\omega)+\frac{q'(a,\omega)}{\omega}p, \quad (2)$$

where $q(a,\omega)$, $q'(a,\omega)$ are coefficients of harmonic linearization, which are determined on the formulas:

$$q(a,\omega)=\frac{1}{\pi a}\int_0^{2\pi}F(a\sin\varphi, a\omega\cos\varphi)\sin\varphi d\varphi, \quad (3)$$

$$q'(a,\omega)=\frac{1}{\pi a}\int_0^{2\pi}F(a\sin\varphi, a\omega\cos\varphi)\cos\varphi d\varphi. \quad (4)$$

Thus, using the harmonic linearization method of the FC system (see Fig. 1) is reduced to the form of Fig. 2, where the frequency response of the equivalent element $W_{HP}(a,j\omega)$ depends only on the amplitude a and does not depend on the frequency ω:

$$W_{FC}(a)=q(a)+jq'(a). \quad (5)$$

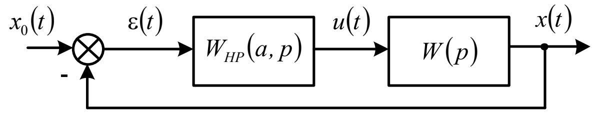

Fig. 2. Harmonic linearization of the ACS

IV. Synthesis Technique of the Fuzzy Automatic Control System the GTE

Consequently, based on the numerical procedure, harmonic linearization of FC is possible. This allows the synthesis of a fuzzy controller under the condition that there are no self-oscillation in the system. So for the guaranteed absence of oscillation in the system, it is enough to satisfy the Golfarb criterion [4]: nonintersection of the locus of the linear $W(j\omega)$ and nonlinear $R_{FC}(a)$ parts of the system on the complex plane.

This condition can be used as a criterion for the stability of a closed system in the development of methods for the synthesis of fuzzy ACS. The performance of fuzzy control systems is determined by the selected rule base. And the quality of processes of control largely depends on the parameters of the membership function of the input and output logic rules (LR) of FC. Therefore, an important step in the synthesis of a FC is the optimal setting of the parameters of the membership functions in accordance with the specified quality criteria of the control process. Thus, the problem of FC synthesis is as follows. It is necessary to adjust the parameters of the membership functions of the FC for a given linear part of the ACS, given the base of fuzzy controller rules, transient quality criteria and stability criterion or a given oscillation index (forbidden zone for the amplitude-phase-frequency characteristic (APFC) of the linear part of the ACS).

Through the simulation, the dependencies of the quality the transient process [8], [9] on the parameters of the membership functions for closed systems with fuzzy PI and PD controllers were revealed:

1) Scaling/compressing the range of the output membership function of a FC leads to an

increase/decrease an initial speed of the transient process.

2) Scaling/compressing the range of the membership function at the first input of the FC leads to a decrease/increase in the transient process time.

3) Scaling/compressing the range of the membership function at the second input of the FC leads to an increase/decrease in the overregulation of the transient process.

The detected dependencies can be used to form the rule base of the expert system, which allows you to configure a fuzzy controller, provided that the specified quality criteria are execute. Since the identified dependencies are formulated in the form of fuzzy statements, for solving this problem it is proposed to use a setting unit that is also built on the basis of a fuzzy logic instruments (Fig. 3).

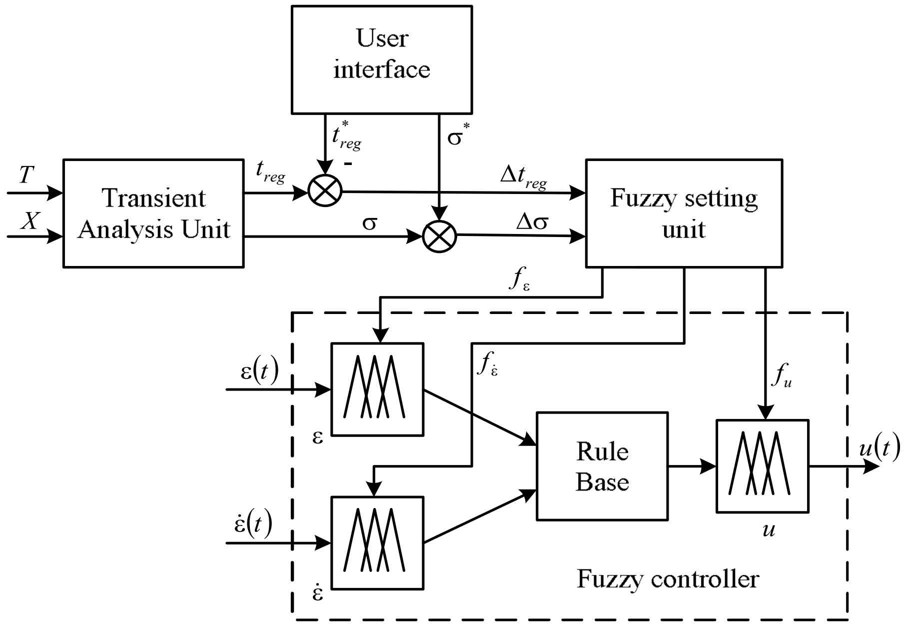

Fig. 3. Configuring a fuzzy controller with a fuzzy expert system: T an array of current time values; X is the array of values of the corresponding transient processes; t^*_{reg}, σ^* is the desired setting time and overregulation value; t_{reg}, σ is the setting time and overregulation value in the synthesized system; Δt_{reg}, $\Delta\sigma$ is the deviation from the desired setting time and overregulated value; f_ε, $f_{\dot\varepsilon}$, f_u are coefficients of setting the membership functions for the error, the speed of the error and the control action

Deviations from the desired values of the overregulated value $\Delta\sigma$ and setting time Δt_{reg} of the transient of the designed system are fed to the inputs of the setting unit. The direct use of these dependencies in the base of rules of a fuzzy settings unit requires a preliminary analysis of the quality indicators of the corresponding transient at the output of the synthesized automatic control system of the GTE. That is implemented by the transient analysis unit.

V. Synthesis of the Propeller Fan Fuzzy Control System

A block diagram of the control system ECS-27 of the D-27 engine for speed channel of propeller fan is shown in Fig. 4. The control object is a coaxial propeller fan CR-27 designed to convert engine torque into thrust.

The coaxial propeller fan CR-27 consists of front (FPF) and rear (RPF) propeller fans, which are connected with the free turbine of the D-27 engine using a differential gearbox.

On the gas-turbine engine operating modes above (small gas mode), the electronic ACS-ESC-27 automatically maintains the set rotational speed of the coaxial propeller fan, adjusting the angles of installation of the blades of the front φ_{FR} and rear φ_{RR} fans.

Changing the angles of installation of the blades of FPF and RPF according to signals from the ESC-27 is performed by the regulator RSV-27.

As an electromechanical energy converter, which provides the transmission of an electrical signal from the ESC-27 to a hydromechanical regulator, a stepper motor DVSh-50 is used. This engine has a local feedback, which monitors the position of the shaft of the stepper motor ψ_{SM} using a DBSCT-220 sensor (non-contact sine-cosine transformer sensor).

The main functions of ACS for control channel of propeller fan D-27:

– installation blades of the propeller fan on the feathering stops, loading, fixing the pitch with a negative thrust, e.t.c.;

– limit the minimum value of positive thrust;

– support of rotational speeds of front n_{FR} and rear n_{ZR} propeller fans under the low:

$$n_{FR}^{set} = n_{RR}^{set} = f\left(R_{mp}, T_{ent}\right), \qquad (6)$$

where n_{FR}^{set}, n_{RR}^{set} - set rotation speed values front and rear propeller fans; R_{mp} is the magnitude of the standard thrust of propeller fans; T_{ent} is the air temperature at the entrance of the GTE.

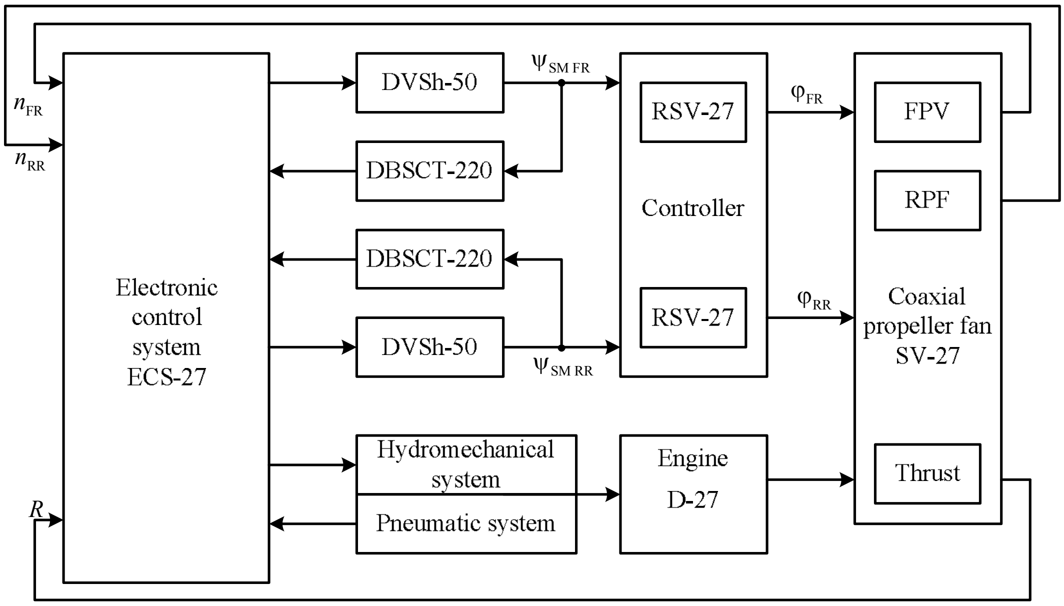

Fig. 4. Control channel of the propeller fan ACS D-27

Requirements for static accuracy of rotational speed support of propeller fans, time of transient t_{reg} and overregulated value σ are 0.5%, 1 s and 0% accordingly. On the processes of acceleration (the transition of the GTE from the small gas go to take-off mode) allowed overregulation value $\sigma = 1\%$ during $t = 3$ s.

The mathematical model of the D-27 is decomposed into two parts: a mathematical model of the gas generator and a mathematical model of the propeller fan [6], which are connected through the power on the shaft of a free turbine N_{FT}. The executive part of the ACS contains a stepper motor (SM), covered by negative feedback, and a hydromechanical regulator PCB-27. Models of stepper motor circuits in the control channels of FRV and RRV can be represented as proportional links with unit gains. The inputs of these links receive the set values of the angles of rotation of the stepper motor $\psi_{SM\,FR}^{set}$ and $\psi_{SM\,RR}^{set}$, deg, which are formed by the speed regulator of the propeller fan, and the outputs are the angular positions of the shafts of the stepper motor $\psi_{SM\,FR}$ and $\psi_{SM\,RR}$ deg.

The angular positions of the shafts of the stepper motor are limited at the level of -30 and +30 degrees. The input parameters of the RSV-27 model are the angular positions of the SM, the output parameters are angles of installation of the blades of the front φ_{FR} and rear φ_{RR} propeller fans.

Nonlinear dependences $\dot{\varphi}_{FR} = F(\psi_{SMFR})$ and $\dot{\varphi}_{RR} = F(\psi_{SM\,RR})$ are the speed characteristics of servo drives of propeller fans and are given as a Table I [6].

During the design an intelligent control system of the propeller fan, the classical structure of the fuzzy control system was also chosen. In this fuzzy control system the fuzzy PD controller is used for direct control of the object. A block diagram of the fuzzy automatic control system of propeller fan is shown in Fig. 5. The following designations are accepted in block diagram: $n_{FR}^{set}(t)$, $n_{RR}^{set}(t)$, $n_{FR}(t)$, $n_{RR}(t)$, $\varepsilon_{FR}(t)$, $\varepsilon_{RR}(t)$, $\dot{\varepsilon}_{FR}(t)$, $\dot{\varepsilon}_{RR}(t)$, $\alpha_{FR}(t)$, $\alpha_{RR}(t)$, $R(t)$, $R^{set}(t)$ - set and current values of rotational speeds, the divergence between the set and current values of rotational frequencies, derivative from the divergence and the control actions of the front and rear propeller fans, current and set values of thrust of the GTE.

To “fuzzify” the magnitude of the regulation error $\varepsilon(t)$ and its derivative $\dot{\varepsilon}(t)$, can be introduced such linguistic variables: LP_1 = "value of error"; LP_2 = "derivative of error". For obtaining the control signal at the output of the FC, let introduce a linguistic variable LP_3 = "control action".

For each linguistic variable, let introduce three values (terms), that is, each of these variables can take the following values (terms):

– "positive large" (*PL*);
– "near zero, optimal" (*Z*);
– "negative large" (*NL*).

Then linguistic variables can be described by a variety of values:

$$L_i = \{NL, Z, PL\}. \quad (7)$$

TABLE I THE SPEED CHARACTERISTICS OF SERVO DRIVES OF PROPELLER FANS

$\psi_{\text{SM FR}}$, deg	-40	-16	-4.8	0	8	16	40
$\dot{\varphi}_{\text{FR}}$, deg	-7.9	-6.3	-3.5	0	4.3	8.2	9.7
$\psi_{\text{SM RR}}$, deg	-40	-16	-4.8	0	8	16	40
$\dot{\varphi}_{\text{RR}}$, deg	-8.9	-7.6	-5.6	0	5.5	8.9	11.6

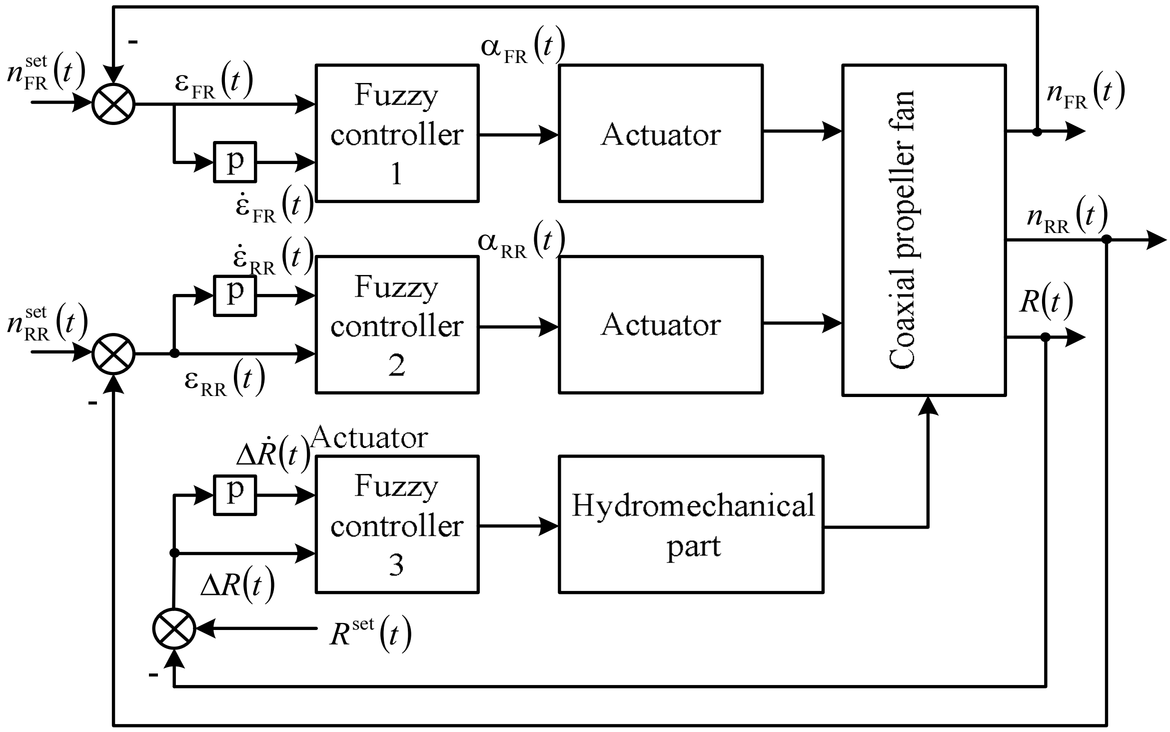

Fig. 5. A block diagram of the fuzzy automatic control system of propeller fan of GTE

As a control algorithm for the implementation in the rule base of a fuzzy controller, the following PD-law was chosen:

1) If ($\varepsilon = PL$ and $\dot{\varepsilon} = PL$) then $\alpha = PL$.
2) If ($\varepsilon = PL$ and $\dot{\varepsilon} = Z$) then $\alpha = PL$.
3) If ($\varepsilon = PL$ and $\dot{\varepsilon} = NL$) then $\alpha = PL$.
4) If ($\varepsilon = Z$ and $\dot{\varepsilon} = PL$) then $\alpha = PL$.
5) If ($\varepsilon = Z$ and $\dot{\varepsilon} = Z$) then $\alpha = Z$.
6) If ($\varepsilon = Z$ and $\dot{\varepsilon} = NL$) then $\alpha = NL$.
7) If ($\varepsilon = NL$ and $\dot{\varepsilon} = PL$) then $\alpha = NL$.
8) If ($\varepsilon = NL$ and $\dot{\varepsilon} = Z$) then $\alpha = NL$.
9) If ($\varepsilon = NL$ and $\dot{\varepsilon} = NL$) then $\alpha = NL$.

The relationship between the input and output linguistic variables is represented by the base of rules in the form "if – then", which can be summarized in the decision table (Table II).

The synthesis of the parameters of the membership functions of the linguistic variables (terms) of the FC for ASC of propeller fan of the aviation GTE was carried out using a fuzzy expert system (see Fig. 3). The membership functions are shown in Figs 6 and 7.

TABLE II THE BASE OF RULES OF A FUZZY CONTROLLER FOR ACS OF PROPELLER FAN

ε \ $\dot{\varepsilon}$	**NL**	**Z**	**PL**
NL	NL	NL	NL
Z	NL	Z	PL
PL	PL	PL	PL

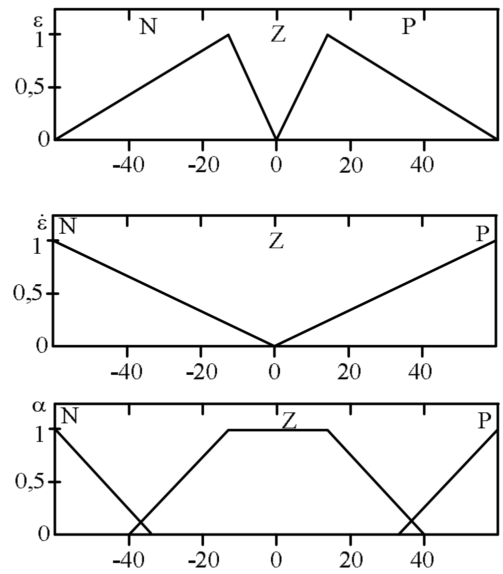

Fig. 6. The membership functions of the FC of the control channels for propeller fan rotational speed: ε is the regulation error; $\dot{\varepsilon}$ is the derivative of regulation error; α is the control action

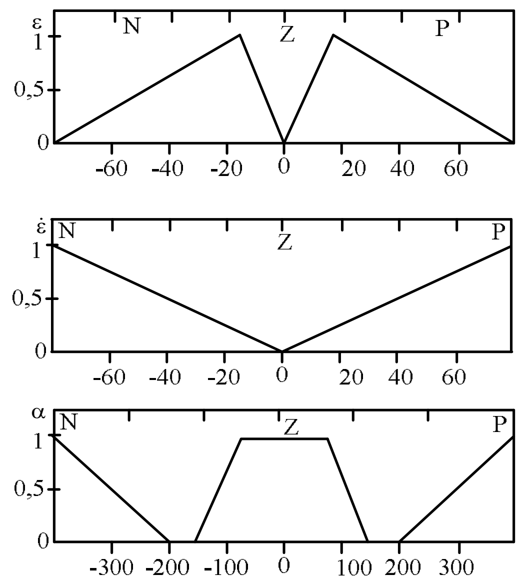

Fig. 7. The membership functions of the FC of the control channels for propeller fan thrust: ε is the regulation error; $\dot{\varepsilon}$ is the derivative of regulation error; α is the control action

VI. CONCLUSIONS

The analysis of the principles of constructing the fuzzy control systems, shown, that the use of fuzzy logic provides a new approach to the design of control systems for aviation GTE and in contradistinction to traditional methods of control, it guarantees the possibility of solving a number of problems in conditions of uncertainty.

It is shown that a fuzzy controller, as the only substantially non-linear element using numerical integration methods, can be linearized by the describing function method. This allows the study of periodic motions in fuzzy ACS. Harmonic linearization method allows the usage the oscillation index to estimate the quality in separate channels of fuzzy ACS for aviation GTEs.

On the basis of the proposed criteria for the stability and quality of control processes, a method for the synthesis of fuzzy control systems has been developed. For optimal tuning of the membership functions of typical fuzzy controllers according to the quality criteria for transient processes, a fuzzy expert system has been developed. The fuzzy laws for the control of a propeller fan of aviation GTE are synthesized. These laws significantly expand the range of quality control in the control channels of rotation speed and propeller fan thrust.

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Received September 20, 2018

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С. В. Єнчев, Т. А. Мазур, С. С. Товкач. Синтез нечіткої системи автоматичного керування гвинтовентилятором авіаційного газотурбінного двигуна

Розглянуто вирішення важливої науково-прикладної задачі – розробка методики синтезу систем автоматичного керування з нечіткими регуляторами. При цьому нечіткий регулятор розглядається як сепаратна підсистема у складі загальної системи керування. Використання методу гармонічної лінеаризації нелінійного елемента – нечіткого регулятора дозволяє проводити синтез системи керування за заданим показником коливальності. На основі проведених досліджень зпроектовано нечітку систему автоматичного керування гвинтовентилятором авіаційного двигуна.

Ключові слова: система автоматичного керування; авіаційний газотурбінний двигун; нечіткий регулятор; гвинтовентилятор; гармонічна лінеаризація.

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С. В. Енчев, Т. А. Мазур, С. С. Товкач. Синтез нечеткой системы автоматического управления винтовентилятором авиационного газотурбинного двигателя

Рассмотрено решение важной научно-прикладной задачи – разработка методики синтеза систем автоматического управления с нечеткими регуляторами. При этом нечеткий регулятор рассматривается как сепаратная подсистема в составе общей системы управления. Использование метода гармонической линеаризации нелинейного элемента – нечеткого регулятора, позволяет проводить синтез системы управления по заданному показателю колебательности. На основе проведенных исследований спроектирована нечеткая система автоматического управления винтовентилятором авиационного двигателя.

Ключевые слова: система автоматического управления; авиационный газотурбинный двигатель; нечеткий регулятор; винтовентилятор; гармоническая линеаризация.

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