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SYNTHESIS OF FUZZY LOGIC CONTROLLER OF NONLINEAR DYNAMIC SYSTEM WITH VARIABLE PARAMETERS

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Abstract: Nonlinear dynamic system with variable coefficients has been considered. For this system, after linearization, a fuzzy controller has been synthesized. Comparison with a traditional controller has been conducted. Corresponding qualitative and quantitative estimates have been provided.

At first, the general approach to the design of controllers of nonlinear systems is described. These theoretical considerations are applied to the design of controllers of linear systems. In this case, the object model is the same in all subsystems of the family. In the case of nonlinear systems, we suggest an approach to the design of controllers that ensures the desired behavior of the system. The paper considers the case when a controller synthesized for one of the subsystems ensures its unstable behavior.

The paper consists of seven sections. In the first section a comparison with existing approaches is done, in the next section a description of the investigated system is given. The third section is devoted to the design of controller that takes into account the nonlinearities of the system, in the fourth section the controller for a linear system with variable parameters is introduces and in the next section a controller of nonlinear system with variable parameters is described. In the sixth section the object that is use as an example in this paper is described. Obtained results are given in the seventh section. The paper ends with conclusions.

Key words: Fuzzy control, robust control, nonlinear system, intelligent control, fuzzy system.

1. Introduction

It is important to consider nonlinearities in the synthesis of control devices for real systems. Traditionally, such systems are linearized in a single point where control actions are synthesized. However, the system features associated with its nonlinear nature are lost in the application of this approach, and a synthesized controller may not always provide adequate transient processes. Most actual systems are nonlinear. Therefore the accuracy of the model and, consequently, the accuracy of the synthesized controller increase with the increased number of nonlinearities, which are simultaneously considered in the system.

Today there are many up-to-date methods of synthesis of controllers for nonlinear systems. Among these approaches one can distinguish, in particular, feedback linearization, geometric methods, LMI-based methods, etc. Paper [1] deals with the systems in the form of a system of the first-order differential equations, the right side of which satisfies the Lipschitz Condition. It has suggested an approach to the controller synthesis relative to a full state vector, which provides stability of a nonlinear system without guaranteeing its desired behavior. For simulation of nonlinear system with uncertain but limited external disturbances in paper [2] it has been suggested that the Takagi-Sugeno fuzzy system and the adaptive control approaches can be combined. However, in this case it requires solving systems of equations at every step of simulation, which may cause difficulties in highly-dynamic systems. The article [3] suggested approaches to synthesis of robust control of nonlinear systems with uncertainties. However, the research is carried out for the systems with “fading memory” feature. The main attention in paper [4] is focused on the issues of stability of nonlinear systems using the apparatus of fuzzy sets, dynamic characteristics not having been studied at that.

The methods applying the apparatus of fuzzy sets have become widely used. In particular, it is suggested in [5] that polynomial fuzzy model based system for approximation of the nonlinear system can be used. It has been proved that this approach allows maintaining the system stability. However, the possibility of improving the dynamic characteristics of nonlinear systems with application of fuzzy controller has not been investigated in the paper.

2. Description of systems using the family of dynamic systems

Let us consider a nonlinear system, which is generally described by the n-th order differential equation. It can be reduced to the system of the first order differential equations

$$\bar{x}'(t) = f\left(\bar{x}(t), q(t)\right) + g\left(\bar{x}(t)\right)\bar{u}(t) + x(t), \quad (1)$$

where $\bar{x}(t) = \left[x_1(t), x_2(t), \mathbf{K}\, x_n(t)\right]^T$,

$x_1(t)=x(t),\ x_2(t)=x'(t)$, $\bar{u}(t)\in R^n$ is the vector of control impacts, $\bar{x}(t)$ are the external disturbing impacts, $f(\bar{x}(t),q(t))$ and $g(\bar{x}(t))$ are the nonlinear functions described in the region of the system operating points, $q(t)$ is the vector of variable parameters that do not depend on $x(t)$. Neglecting external disturbances and using the first addend of Taylor expansion by $x(t)$ of the right-hand side, this system can be linearized in several points. As a result, we obtain a linear model with variable parameters. The domain has been divided into n subdomains according to the number of linearization points, and a general nonlinear system model has been created with a set of n fuzzy rules of the form:

$$R^i:\ IF\ \ x_1\in M_1^i\ i\ x_2\in M_2^i\ i\ \mathbf{K}\ x_n\in M_n^i\ THEN$$
$$\dot{\bar{x}}(t)=A_i(q)\bar{x}(t)+B_i\bar{u}(t),\quad i=\overline{1,n}, \tag{2}$$

where R^i is the i-th rule, $M_j^i, N_j^i,\ i=\overline{1,k},\ j=\overline{1,n}$ are the domains of division, $A_i(q), B_i\in R^{n\times n}$ are matrices forming the model of the system around some operating point (local model) relative to some q. This paper considers an instance when $A(q+\Delta q)=A(q)+A(\Delta q)$. Provided that q changes its value over time within some a priori known limits, it is possible to find the values of matrix $A(q_i)$ in separate points $q_i\in[q,q+\Delta q]$. The number of points of division can be chosen using consideration from Section 4 of this article.

Therefore, the model of the i-th system will have the following form

$$\dot{\bar{x}}(t)=A_i+B_i u(t). \tag{3}$$

Thus, in fact, we obtained a family of linear dynamic systems (3).

The case of control by the full state vector for each of the subsystems has been studied in the paper. The controller of the general system has been obtained using fuzzy logic apparatus

$$R^i:\ \ IF\ x_1\in N_1^i\ i\ x_2\in N_2^i\ i\ \mathbf{K}\ x_n\in N_n^i\ THEN$$
$$\bar{u}(t)=K_i\bar{x}(t),\qquad j=\overline{1,n}, \tag{4}$$

where $K_i\in R^{n\times n}$ are matrices determining the tuning of the i-th system controller to a particular standard linear form.

A gravity defuzzification method has been used to obtain the following model of the system

$$\dot{\bar{x}}(t)=\sum_{i=1}^{k}n_i(\bar{x})\left(A_i+B_i\sum_{j=1}^{k}m_j(\bar{x})K_j\right)\bar{x}(t), \tag{5}$$

where $n_i=n_i(\bar{x})=\dfrac{\prod_{j=1}^{n}M_j^i(x_j(t))}{\sum_{i=1}^{k}\prod_{j=1}^{n}M_j^i(x_j(t))}$,

$m_i=m_i(\bar{x})=\dfrac{\prod_{j=1}^{n}N_j^i(x_j(t))}{\sum_{i=1}^{k}\prod_{j=1}^{n}N_j^i(x_j(t))}$, $M_j^i(x_j(t))$, $N_j^i(x_j(t))$ are functions of $x_j(t)$ membership to corresponding sets (either M_j^i or N_j^i), $\sum_{i=1}^{k}n_i=1,\ \sum_{i=1}^{k}m_i=1$.

For investigating the stability of such systems a following theorem has been proved [6].

Theorem. If we select matrices $K_i,\ i=\overline{1,k}$ so that systems (3) are Lyapunov stable and

$$\sum_{j=1}^{k-1}\sum_{i=j+1}^{k}\left\{\left[\left(K_i-K_j\right)\left(n_j m_i B_j-n_i m_j B_i\right)\right]^T\times\right.$$
$$\left.\times P+P\left(K_j-K_i\right)\left(n_j m_i B_j-n_i m_j B_i\right)\right\}>-\sum_{i=1}^{k}\bar{Q}_i, \tag{6}$$

where $\bar{Q}_i>0,\ i=\overline{1..k}$, P matrix is connected with all the systems, $P=\prod_{i=1}^{k}P_i$, system (1) is also Lyapunov stable.

The following sections consider the issues of the controllers synthesised for the obtained subsystems.

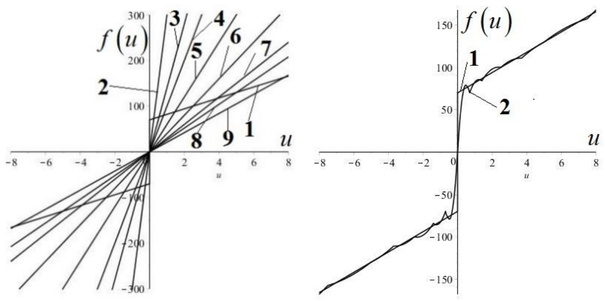
3. Synthesis of the system controller taking into account nonlinearities

In the electrotechnical systems for approximation of nonlinearities, the function is traditionally approximated with a line $f(u)\approx f_1(u)=K_{tp}^1 u$, by decomposing this nonlinear function into the Taylor series at the origin of coordinates, and ignoring the addends above the second order. However, this approximation is valid only in a small region of the variation of input voltage argument (see Fig. 1, *a*, lines 1 and 2). In [7] and [8] it has been proposed that fuzzy logic apparatus can be applied to approximate the function.

Depending on the input signal value, nonlinearity is approximated as follows (see Fig. 1, *a*, lines 2–9)

$$f(u)\approx\sum_{i=1}^{n}m_i(u)K_{tp}^i u,\ i=\overline{1..\text{n}},\ K_{tp}^i>K_{tp}^{i+1}, \tag{7}$$

where $m_i(u)$ is the membership function that is defined below. The graphs of exact and approximate value of the nonlinear function are shown in Fig. 1, *b*, lines 1 and 2.



a) *b)*

Fig. 1. Approximation of the bias function with the help of the fuzzy logic apparatus: a) traditional version 1- curve from (3), 2–9 lines $f_i(u) = K_{tp}^i u,\ i = \overline{1...n},\ K_{tp}^i > K_{tp}^{i+1}$ b) with the application of fuzzy logic.

The Takagi-Sugeno fuzzy controller [9] was applied to implement the proposed approach. For the linguistic variable "argument" and its terms $U_i,\ i = \overline{1...n}$ we shall use a triangular membership function (see [10, pp. 46–65]). Defuzzification is to be conducted with the simplified gravity method. So, we shall obtain

$$IF\ (u\ in\ U_i)\ THEN\ \bar{u}(t) = g_i(\bar{x})$$

$$u(\bar{t}) = \sum_{i=1}^{n} m_i(t)\, g_i(\bar{x}) \quad (8)$$

$$g_i(\bar{x}) = K_i \bar{x}(t), \quad i = \overline{1...n}$$

where $g_i(\bar{x})$ are proper functions of the state vector of the system, U_i are regions of division. The respective controller was synthesized for each of the functions $g_i(\bar{x})$ by the full state vector and K_i defines the tunings for a particular standard linear form. This paper studies the case of tuning for a standard linear binomial form and the Bessel form. Just one variable is fuzzified if this approach is used, so the number of rules is equal to the number of divided regions. The increased number of rules results in the increased accuracy on the one hand, while making the controller more complex on the other, as more rules need to be synthesized. On the contrary, there is an option of using fewer rules to simplify the controller, for instance, only for boundary and several interior points. The system dynamics will get somewhat worse at that.

4. Synthesis of the controller for linear system with variable parameters

There are many approaches to synthesis of robust control for the system with variable parameters, including predictive control (MPC; see. e.g., [11]), optimal robust control [12], and fuzzy robust control proposed by the authors.

It is well known that a robust controller is the controller ensuring adequate quality of control, for example, a stability margin if the object of control differs from the estimated one. The controller synthesized for some value x_L^j of the variable $x_L \in \left[x_L^0; x_L^N\right]$ has a certain stability margin, i.e., when a real value of the variable x_L deviates from x_L^j for some value $r\left(x_L^j\right)$, the system remains stable. This value is called the radius of stability (see, e.g., [13, pp. 186–221]). If $\Delta x_L^i = x_L^{i+1} - x_L^i > r\left(x_L^i\right)$, the system loses its stability. To determine the stability radius of the system one can use, for instance, the Tsypkin-Polyak locus. The value of parameter x_L can be determined by applying, for example, the extended Kalman filter or Luneburg determinant. Moreover, the value of x_L can be determined basing on the position of some electromechanical systems like an auger, robotic arm, etc. (see e.g. [14]).

The idea of the suggested approach consists in the synthesis of the control actions with such x_L^i values so that $x_L^{i+1} < x_L^i + r\left(x_L^0\right)$, which will ensure the robustness of the whole system. Thus, we will actually switch from the studied system to the family of sub-systems with the same control object and various control actions. The apparatus of the theory of fuzzy sets will be used for smooth switching between the subsystems.

Designing the fuzzy controller for the studied system, we should firstly specify its main degrees of freedom. Defuzzification will be conducted with the simplified gravity method. In general, the i[th] rule has the form

$$R_i:\quad IF\ x_r\ in\ XL_i\quad THEN\quad \bar{u} = K_i \bar{x}, \quad (9)$$

where x_r is the output signal of the second mass integrator, XL_i is the term of the corresponding fuzzy variable, K_i is a matrix synthesized for $x_L = x_L^i$ value.

The membership function depicted in Fig. 2 has been used for fuzzification.

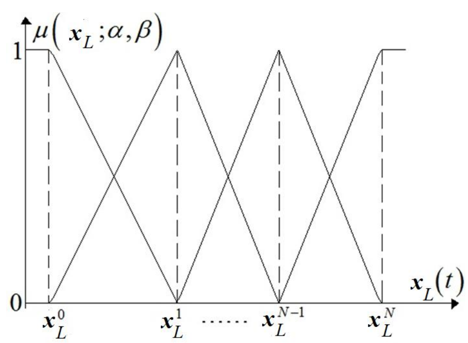


Fig. 2. Membership function.

If the system has several variable parameters, we can consider each of them similarly and apply a fuzzy controller, which will take into account a simultaneous change of these parameters as it is shown below.

5. Nonlinear system with variable parameters

This paragraph simultaneously considers both the nonlinearity in the system and a possibility of changing one of its parameters. In this case, both approaches from the previous paragraphs are simultaneously applied. It is necessary to synthesize a controller with two inputs and one output. The output signal of the controller will take the following form

$$u_{fuz}(\bar{t}) = \sum_{a} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} n_i(t) m_j(t) K_{ij}^{a}}{\sum_{i=1}^{n}\sum_{j=1}^{n} n_i(t) m_j(t)} \bar{x}_a(t) \qquad (10)$$

where n_i, m_i are membership functions obtained after fuzzification described in the previous paragraphs.

It should be noted that the membership function was not optimized in this article as it was in [15].

A general flow diagram of the studied object is shown in Fig. 3

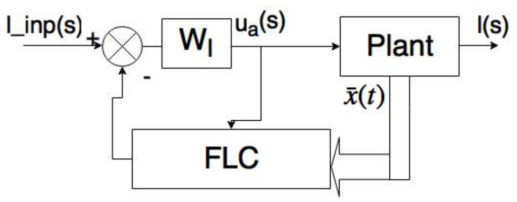


Fig. 3. Flow diagram of the studied system.

FLC (Fuzzy-Logic Controller) element is responsible for the fuzzification of the input voltage of a thyristor converter and the moment of inertia of the second mass; it contains the relevant rule base.

6. Object of the research

Many technological systems use two-mass model for description, where the first mass is responsible for the integral inertia moment of the motor, and the second mass – for the load inertia moment. Detailed description of the two-mass systems is given in [16, 17]. It should be noted that an arc furnace can be mentioned among many objects corresponding to the studied model [14, 15].

Classical methods of analysis of such systems do not take into account parameter variance, thus it is impossible to use them in this case. A main question that appears at dynamical system analysis is stability. To investigate this problem we use results from [6].

A real model of the system contains many nonlinear components. Consideration of all of them leads to significant complications of the simulation process. Therefore, we neglect some of nonlinearities in this paper, in particular, the Coulomb friction (see [8]). The mathematical model of the electric component of the system (Fig. 4) is described the following way

$$\begin{aligned} &v_a(t) = R_a(t) i_a(t) + L_a(t)\left(\frac{di_a(t)}{dt}\right) + e_a(t) \\ &e_a(t) = K_b w_m(t), \quad T_m(t) = K_m i_a(t) \\ &v_a(t) = f\left(v_m(t)\right) \end{aligned} \qquad (11)$$

where $v_a(t)$ is motor armature voltage, $R_a(t)$ $[\Omega]$ is armature resistance, $L_a[\mathrm{H}]$ is armature inductance, $i_a(t)[A]$ is armature current, $e_a(t)[V]$ is back electromotive force, $K_m[Vs/\mathrm{rad}]$ is a motor torsion constant, $K_b[Vs/\mathrm{rad}]$ is a motor velocity constant, $T_m(t)[Nm]$ is torque caused by the motor, $w_m(t)[\mathrm{rad}/s]$ is angular motor rotational velocity, $f(v_m)$ is a nonlinear function, which corresponds to the thyristor voltage converter model, v_m is the input voltage of the thyristor converter.

It is well known that in such a system the following parameters may vary: ΔR (resistance of armature windings due to motor's parts heating); ΔL (armature inductance when the flux is not constant); ΔJ (moment of inertia of the mass on the end of the shaft).

Further we are going to consider the case of an ideal motor, i.e., when $K_m = K_b$.

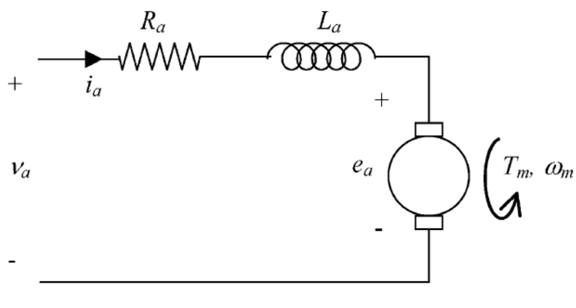


Fig. 4. The electric component of the mechatronic system.

We also neglect the nonlinearities in the mathematical model of mechanical part, such as backlash in the gear. The linear model of the mechanical part of the system (Fig. 5) is described as follows

$$\begin{aligned} &J_m\left(\frac{dw_m(t)}{dt}\right) = (N)^2 T_m(t) - \frac{1}{N} T_s(t) - \frac{1}{N} B_m w_m(t), \\ &J_L(t)\left(\frac{dw_L(t)}{dt}\right) = T_s(t) - B_L w_L(t) - T_d, \\ &T_s(t) = k_s\left(\frac{1}{N} q_m(t) - q_L(t)\right) + B_s\left(\frac{1}{N} w_m(t) - w_L(t)\right), \\ &\frac{dq_L(t)}{dt} = w_L(t) \end{aligned} \qquad (12)$$

$$\frac{dq_m(t)}{dt}=\frac{1}{N}w_m(t),\quad \frac{dq_L(t)}{dt}=w_L(t), l_{out}(t)=rq_L(t),$$

where k_s [Nm/rad] is the coefficient of elastic deformation, B_m and B_L [Nm/(rad/s)] are the coefficients of internal viscous motor friction and load respectively, B_s [Nm/(rad/s)] is internal damping coefficient of the shaft, J_m and J_L [kg m[2]] are the moments of inertia of the motor and the working gear (load), w_m and w_L [rad/s] are angular and rotational velocities of the motor and the end-effector respectively, T_m T_d [Nm] are torques of the motor and the load (end-effector), T_s [Nm] is carried over torque of the shaft, $1/N$ is a reduction ratio.

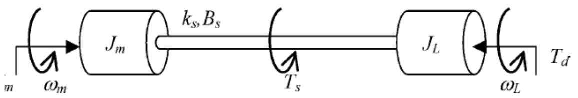


Fig. 5. The mechanical part of the studied system.

In this case, the matrix of the system recorded in the state space looks like

$$A=\begin{pmatrix} -\frac{R_a(t)}{L_a(t)} & -\frac{f(v_m(t))}{L_a(t)} & 0 & 0 & 0 \\ \frac{f(v_m(t))}{J_m} & \frac{-B_s/N^2-B_m}{J_m} & -\frac{1}{N*J_m} & \frac{B_s}{N*J_m} & 0 \\ 0 & \frac{k_s}{N} & 0 & -k_s & 0 \\ 0 & \frac{B_s}{N*J_L(t)} & \frac{1}{J_L(t)} & \frac{-B_s-B_L}{J_L(t)} & 0 \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix} \quad (13)$$

The research on cases of nonlinear system with $J_L = const$ and linear system with variable moment of inertia was conducted in [7, 15]. The research results show that the suggested approaches can provide the desired system behavior and consider the peculiarities of their models.

The research will be conducted for the case when in the process of use the second mass moment of inertia value undergoes changes. This may occur, for example, in the process of soil scooping by an excavator, during freight shifting by a robotic arm, or, for instance, when a helical conveyer transfers grain.

7. Research results

To compare the system performance with synthesized controllers, the value of the index of integral performance and penalty function has been calculated.

$$I^* = I + F_{penalty} =$$
$$=\left(g_1\int_0^T t\left|e(t)\right|dt\right)+\left(g_2\left(\frac{w_M(t)}{w_{M,\max}}\right)^2 H\left(\frac{w_M(t)}{w_{M,\max}}\right)+\right.\quad (14)$$
$$\left.+g_3\left(\frac{v_{out}(t)}{v_{out,\max}}\right)^2 H\left(\frac{v_{out}(t)}{v_{out,\max}}\right)\right),$$

where I is classical integral performance index (see [16], [17], for instance), where $H(\cdot)$ is the Heaviside function, $w_{M,\max}, v_{out,\max}$ are specified maximum permissible overshoots and in the present case they make up to 10 % and 5 % respectively. Coefficients $g_i, i=\overline{1...5}$ have been chosen for the reasons of mutual proportionality of the studied variables.

Fig. 6 simultaneously shows the change in time of the input signal and the change of the time constant value of the second mass $J_L(t)$. Since the extent of changes of each value is different, and it is convenient to put them on one graph, the latter is given in relative units for illustrative purposes. It should be noted that the value of the integral performance index was calculated for the interval of change of the input signal separately: I_i at given $t\in[t_i, t_{i+1}]$.

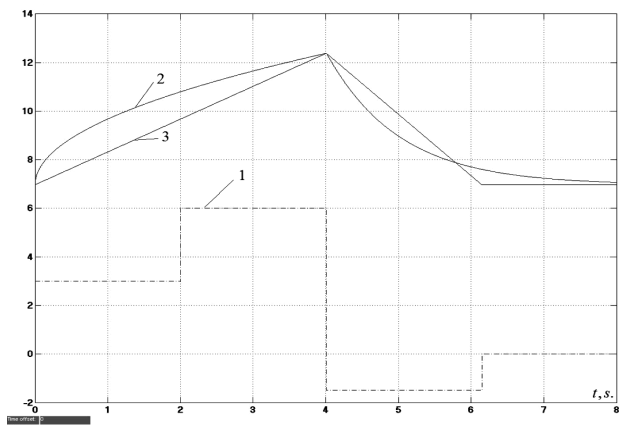
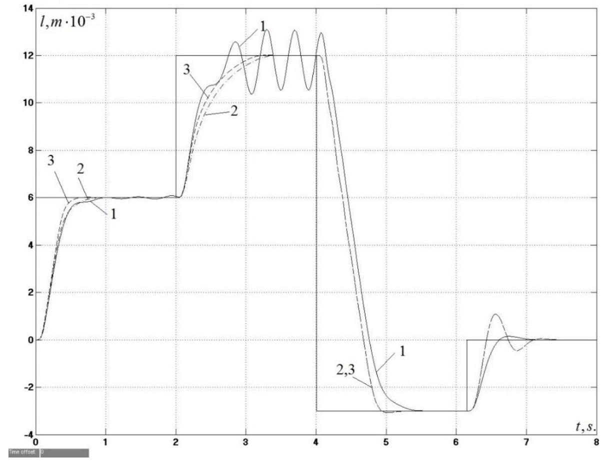


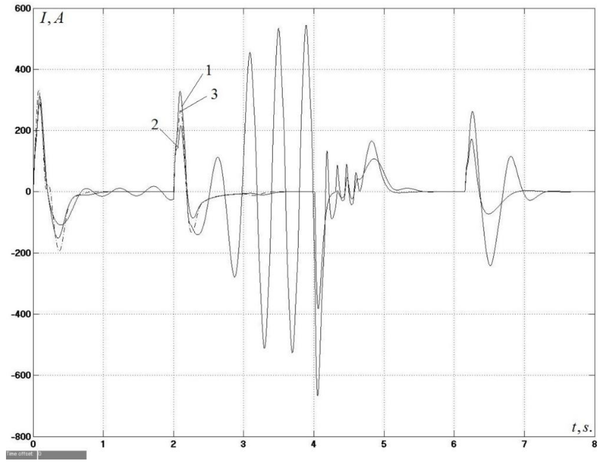
Fig. 6. 1 – System input signal; 2 and 3 – nonlinear and linear functions $J_L(t)$ respectively.

The research has been conducted for the case of simultaneous consideration of nonlinear thyristor converter and the possibility of changing the parameter which is responsible for the load inertia on the motor shaft. The simulation results for the case when the value of inertia of the second mass changes nonlinearly (see Fig. 7) and linearly (see Fig. 8) are provided.

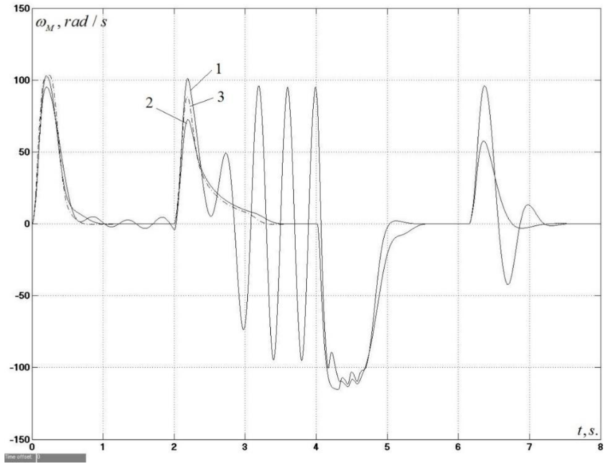
The results demonstrate the applicability of fuzzy logic to the synthesis of the controller for nonlinear systems with variable coefficients, since in this case characteristics of the dynamic system are improved in comparison with the classical approach.



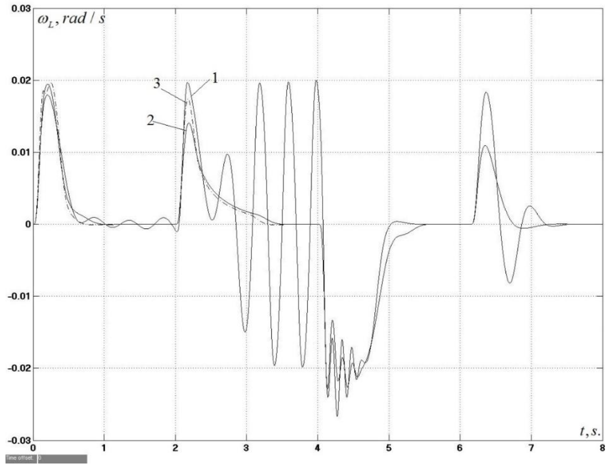
a)



b)

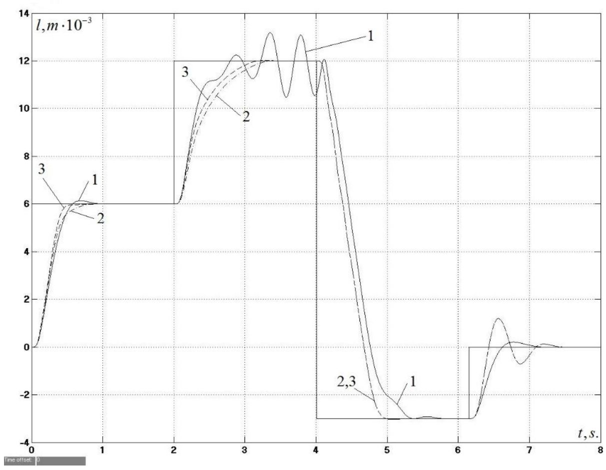


c)

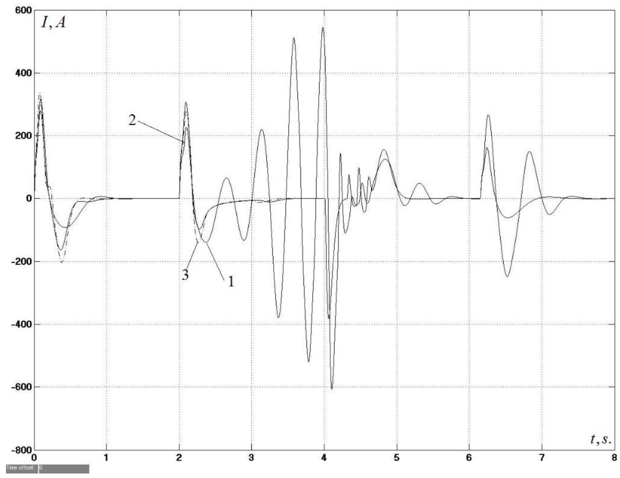


d)

Fig. 7. Simulation result for the case of nonlinearity of the law of variation of the moment of inertia of the second mass: a) system output signal; b) current in the motor anchor; c) angular velocity of the motor shaft rotation; d) angular velocity of the second mass rotation.

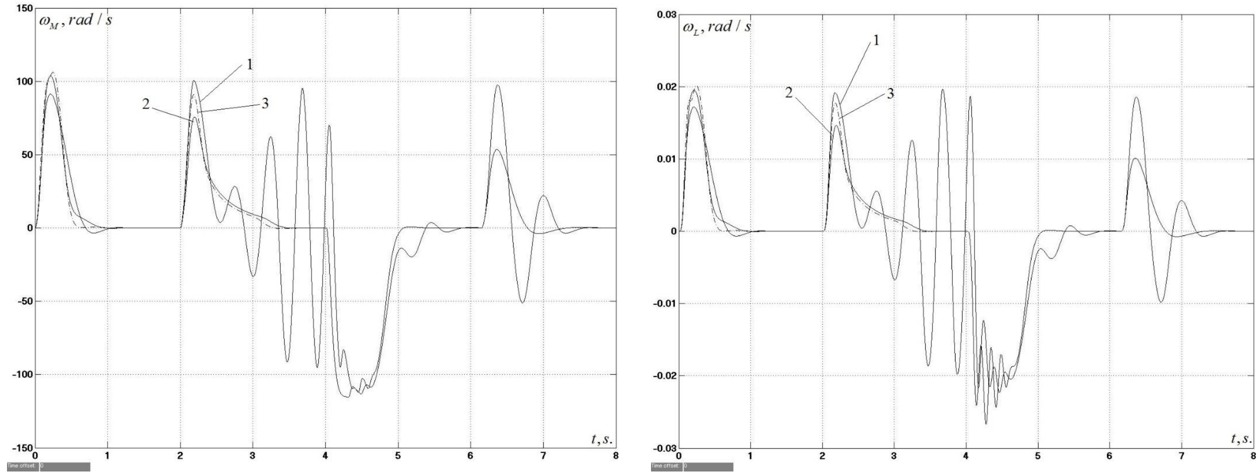


a)



b)

Fig. 8. Simulation result for the linear law of variation of the moment of inertia of the second mass: a) system output signal; b) current in the motor anchor.



c) *d)*

Continuation of fig. 8. Simulation result for the linear law of variation of the moment of inertia of the second mass: c) angular velocity of the motor shaft rotation; d) angular velocity of the second mass rotation.

8. Conclusion

In this article the application of the approach based on the family of dynamic systems has been suggested, where the nonlinearity of the object and the change of the parameters of the object have been considered. The conducted studies prove the feasibility of applying this approach, which is based on the use of the fuzzy set theory to the synthesis of controllers for nonlinear systems with variable coefficients.

Table 1

Performance indexes for investigated system

Type of controller	Behaviour of the second mass time constant value									
	Nonlinear					Linear				
	I_1	I_2	I_3	I_4	I	I_1	I_2	I_3	I_4	I
Linear binomial	93.04	219.4	12.93	0.6196	325.99	221.5	208.4	13.38	0.7094	443.99
Fuzzy Binomial	1.54	3.708	9.64	0.9398	15.83	1.473	3.578	9.629	1.163	15.84
Fuzzy Bessel-Binomal	**1.232**	**2.927**	**9.64**	0.9398	14.74	1.195	2.824	9.629	1.163	14.81

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СИНТЕЗ НЕЧІТКОГО РЕЗУЛЯТОРА ДЛЯ НЕЛІНІЙНОЇ ДИНАМІЧНОЇ СИСТЕМИ ЗІ ЗМІННИМИ КОЕФІЦІЄНТАМИ

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Описано загальний підхід до синтезу регуляторів нелінійних систем. Наведено теоретичні викладки, що їх спочатку застосовано для синтезу регуляторів лінійних систем. У такому разі модель об'єкта буде однаковою в усіх підсистемах сімейства. У випадку нелінійних систем наведено підхід до синтезу регуляторів, що забезпечують бажану поведінку системи як у випадку сталих, так і змінних параметрів. Також розглянуто випадок, коли регулятор, синтезований для однієї з підсистем, забезпечує її нестійку поведінку.

Розглянуто нелінійну динамічну систему зі змінними коефіцієнтами. Для цієї системи, після лінеаризації, було синтезовано нечіткий регулятор. Проведено порівняння з випадком застосування традиційного регулятора. Наведено відповідні якісні та кількісні оцінки.

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