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Electromechanical positioning system with a neuro-fuzzy corrector

***Abstract**. Triple-loop elecromechanical positioning system with neuro-fuzzy corrector of position controller was developed. The structure of the neuro-fuzzy corrector has been grounded and the corrector itself has been designed. A computer Simulink model of a triple-loop two-mass positioning system has been developed. Statics and dynamics of the positioning process in a full range of reference signals and disturbances has been examined. The results of computer simulations demonstrate that the developed positioning system allows implementing optimal laws of actuator's motion, and required positioning accuracy in a full range of reference signals and disturbances.*

Streszczenie.** Przedstawiono elektromechaniczny system pozycjonowania ze sterowanie wykorzystującym logikę rozmytą. Przeprowadzono symulację układu i analizę właściwości statycznych i dynamicznych. Analizowano treż wpływ zakłóceń. **Elektromechaniczny system pozycjonowania ze sterowaniem wykorzystującym logikę rozmytą

Keywords: positioning, fuzzy corrector, neural network, overshoot, computer model.
Słowa kluczowe: system pozycjonowania, logika rozmyta.

Introduction

Crucial precision electromechanical systems (EMS) should meet strict requirements to implement the desirable laws of actuator's motion, as well as for statics and dynamics of the output and intermediate variables.

Electrical and mechanical subsystems of positioning drives can be complex multiloop systems; their kinematic components are often characterized by limited elasticity, include backlashes, air gaps and nonlinearities.

The problem of synthesis of optimum dynamics and high precision statics of robotic devices, mechanisms of metalworking machines, is of great interest. Thus, in [1] and [2], the traditional synthesis is applied, and studies on the dynamics of triple-loop cascade control systems are performed while operating with different structures of position controllers: optimum proportional, parabolic, linear-parabolic variable-structure, sliding-mode controllers of intermediate coordinates. In those works, the laws of motion are studied; the focus is on the features of refinement of small, middle and large movements taking into account the motion tachogram. However, such structures of a positioning control system fail if optimal actuator dynamics should be obtained while operating with different reference signals, parametric and signal disturbances; in particular, backlashes and limited elasticities of kinematics components of the drive's mechanical subsystem. Otherwise, solving these problems requires a significant complication of controllers for all variables [3]–[4].

A model of precision positioning control based on penalty matrices for the quadratic functional is proposed in [5]. The model provides the proper intensity of system reaction decrement; however, aperiodic system reaction cannot be obtained. The system is also oversensitive to destabilizing parametric and signal disturbances.

Perfect statics and dynamics of the systems are obtained using classical, traditional methods of control theory only if the complexity of mathematical representation of such systems is as high as the complexity of the systems. However, after crossing the specific threshold of the mathematical representation complexity, the classical synthesis methods are inapplicable.

In [6], the improvement of control law for a positioning drive based on permanent magnet synchronous motor to account elastic constraints is proposed. The control relies on correcting the standard setting of a speed controller. The proposed technique is based on the approaches of linear control theory. The presence of real backlashes, air gaps, parameter variation during the positioning is unconsidered; therefore, the dynamics is unpredictable.

Advanced information technologies, in particular, methods of fuzzy and neural-network control, are well suited for solving the above-mentioned problem with the suitable compromise between accuracy and complexity. They require no accurate mathematical models of objects and systems, while control synthesis is based on experimental data, expert knowledge and judgment. Their utilization based on fuzzy or incomplete input information about the system state, effective on-line variation of control signals adopted to disturbances is obtained [7]–[8].

Mathematical model of a complex positioning EMS

Plant positioning mechanism can be characterized by the presence of considerable nonlinearities, *i.e.* backlashes and air gaps, *etc*. [9]. Control in such complex system cannot be formalized; positioning is performed under uncertainty and incomplete information, in particular, under the complex law of changing of resulting load torque and inertia, under outer disturbances.

In [10], we demonstrated an example of substantially nonlinear and of a high order mathematical model of a positioning mechanism; therefore, the mechanism is unsuitable for the synthesis of the optimal positioning control utilizing the classical methods. In [11]–[15], a number of solutions of the realization of fuzzy positioning models are proposed and grounded. The studies are performed under different references and disturbances. The obtained simulation results demonstrated that positioning dynamics improved utilizing different fuzzy control models as compared with classic controllers, in particular, PD-controllers [11].

The aim of the work is the development of the synthesis of positioning controller under full range of positioning angles, providing an optimal law of plant's motion under parametric and coordinate disturbances utilizing fuzzy and neural-network control.

The novelty of the work is a neuro-fuzzy model of the synthesis of correcting signal for the position controller (PC) of a positioning EMS. Positioning system based on the proposed design approach is utilized to provide the desired dynamics under the full range of reference signal change and under real coordinate and parametric disturbances.

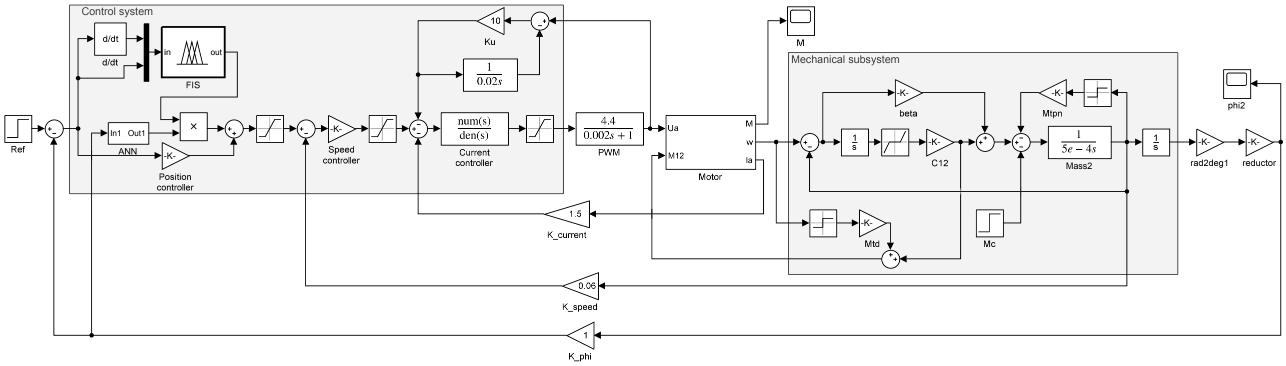

Fig.1. Structure of the Simulink-model of the two-mass positioning EMS with tripple-loop cascade control and with neuro-fuzzy corrector of proportional position controller: Ref—reference signal, ANN—artificial neural network, FIS—fuzzy inference system

Results and Discussion

Taking into account the abovementioned consideration, the structure of the positioning control was selected as triple-loop cascade with a proportional PC and fuzzy corrector [16]. The developed Simulink model of the designed positioning EMS is demonstrated in Fig. 1. The simplified functional block diagram of a proportional PC with neuro-fuzzy corrector is demonstrated in Fig. 2.

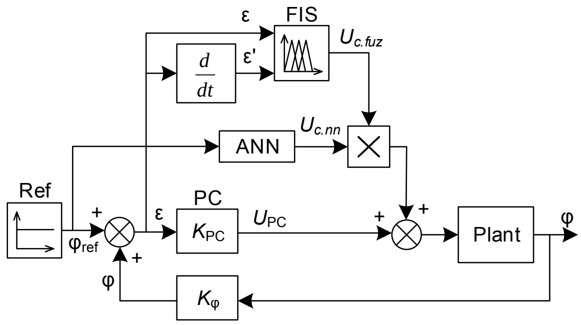

Fig.2. Simplified functional block diagram of positioning electric drive with neuro-fuzzy corrector: Ref—reference signal, PC—position controller, ANN—artificial neural network

For a position loop, a plant is a double-loop cascade control system "PWM converter—DC motor" for electric drive speed control consisting of a two-mass model of a mechanical subsystem, with a proportional-integral current controller and a proportional speed controller [16]. We proposed its application in order to obtain superior statics and dynamics. A position sensor is realized on the rotary position sensor AS5045-ASSU with a gain K_{φ} (Fig. 2). It is a programmable board mount Hall effect magnetic 12-bit rotary encoder in a 16-pin SSOP package used for accurate angular measurement over a full turn of 360°.

We performed experimental studies [10] required for the examination of statics and dynamics of the complex control system, as well as structural and parametric identification of a plant. The obtained parameters and structures were realized in a Simulink model of a control system. In [16] the developed model is validated by comparing the simulated and experimentally obtained reactions on standard references and disturbances.

The obtained reactions $\varphi(t)$ on references within their required range utilizing a proportional PC had demonstrated oscillations with different overshoot and damping (see Fig. 3, curve 1 for $\varphi_{ref} = 30^{o}$). The problem of improvement of plant's dynamics and bringing the quality of positioning dynamics to the required has been solved by grounding the structure of a fuzzy corrector of the proportional PC (Fig. 2) using the Mamdani fuzzy model, its algorithmic and parametric degrees of freedom.

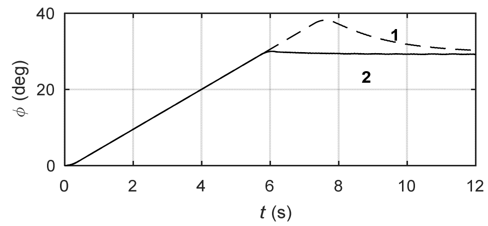

Fig.3. Reaction $\varphi(t)$ for a step control signal $\varphi_{ref} = 30^{o}$: 1 – without fuzzy corrector, 2 – with fuzzy corrector.

We have selected a control error of a positioning angle φ $\varepsilon = \varphi_{ref} - \varphi$, where φ_{ref} is a reference signal, and the error derivative $\varepsilon' = d\varepsilon/dt$ as an input information for the synthesis of correction signal $U_{c.fuz}$. The signal, being obtained from a fuzzy inference system *FIS*, is added to the output signal of a proportional PC U_{PC} in a sum block *S*. The output signal of the sum block *S* is a speed reference—an input for a proportional speed controller (Fig. 2).

Input linguistic variables of the FIS are ε— "Error" and its derivative ε'— "D-Error". After the monitoring of simulation results, we have substantiated five linguistic terms; those are NL—Negative Large, N—Negative, Z—Zero, P—Positive, and PL—Positive Large, as well as their ranges $\varepsilon \in [-70,\ 70]$ and $\varepsilon' \in [-25,\ 25]$. The shape of the limiting terms NL and PL have been selected to be trapezoidal *tramf*, while for inner terms N, Z, P—triangular *trimf* (Fig. 4).

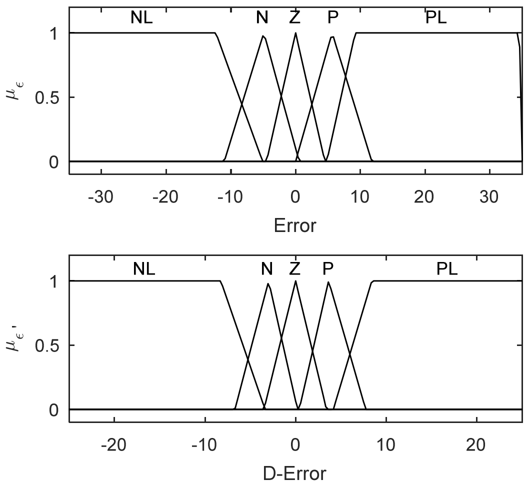

Fig.4. Membership functions of the input variables Error and D-Error

FIS output correcting signal $U_{c.fuz}$ is designed using nine linguistic terms: NL—Negative Large, NM—Negative Middle, NS—Negative Small, N—Negative, Z—Zero, P—

Positive, PS—Positive Small, PM—Positive Middle, PL—Positive Large; its ranges are $U_{c.fuz} \in [-70,\ 70]$. Similar to the input variables, the shape of the limiting terms NL and PL have been selected to be trapezoidal *tramf*, while for inner terms—triangular *trimf* (Fig. 5).

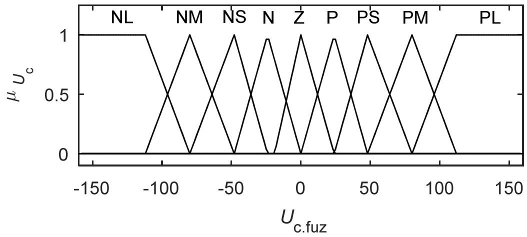

Fig.5. Membership functions of the output variable $U_{c.fuz}$

The FIS rule base is composed on the analysis of the error $\varepsilon(t) = \varphi_1(t) - \varphi_2(t)$ between the real $\varphi_1(t)$ and preferable $\varphi_2(t)$ reactions on the input reference signal and its derivative $\varepsilon'(t)$ (Fig. 3 demonstrates the dependence $\varphi_1(t)$ while curve 2 is identical to $\varphi_2(t)$). The designed rule base has been refined by the quadratic criterion

(1) $$\int_0 \left(\varphi_1(t) - \varphi_2(t)\right)^2 dt \Rightarrow \min$$

The designed rule base, providing an optimal dynamic for the positioning with $\varphi_{ref} = 30^{\circ}$ is demonstrated in Table 1.

Table 1. Fuzzy rules base FIS

		Control error (Error)				
		NL	*N*	*Z*	*P*	*PL*
Control error derivative (D–Error)	*NL*	PL	PL	Z	N	NS
	N	PM	PS	Z	Z	N
	Z	PS	P	Z	Z	N
	P	Z	Z	Z	N	NM
	PL	PS	P	Z	NS	NL

The implication is based on the *min*-operator; aggregation—on the *max*-operator; defuzzification is realized using the *centroid* model.

3D surface of the designed fuzzy corrector FIS for the positioning with $\varphi_{ref} = 30^{\circ}$ is demonstrated in Fig. 6. The obtained reaction on the step reference signal is almost identical to the preferable law of motion (Fig. 3, curve 2).

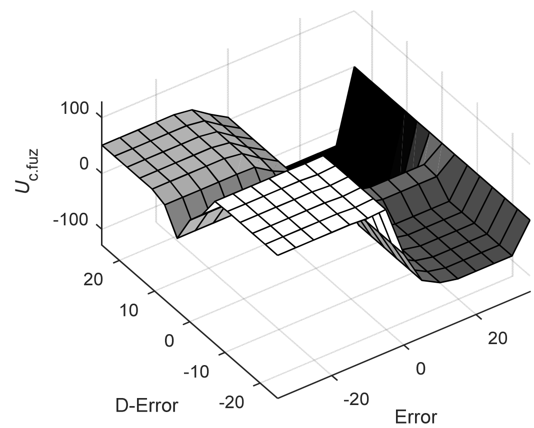

Fig.6. 3D surface of the designed fuzzy corrector FIS

The studies of the reactions $\varphi(t)$ on different step reference signals were performed on the Simulink model with FIS designed for the positioning angle of 30º. It has been observed that reactions on the positioning angles other than 30º are characterized by overshoots and dragging modes, therefore, the positioning time increases. Although, it is worth mentioning that the positioning quality when using fuzzy corrector is better than in a triple-loop system without it.

In order to obtain the desired law of plant's motion when positioning at any angle within the range $\varphi \in [5^{\circ}, 70^{\circ}]$, we propose an online adaptation of a FIS corrector to the reference signal φ_{ref}. The model of the adaptation is based on the ranging of the correcting signal $k_{ac} \cdot U_{c.fuz}$, where k_{ac} is the factor of adaptation of output correcting signal to the reference positioning angle. The model of the adaptation $k_{ac}(\varphi_{ref})$ has been obtained from the Simulink model from the number of simulation experiments (Fig. 7).

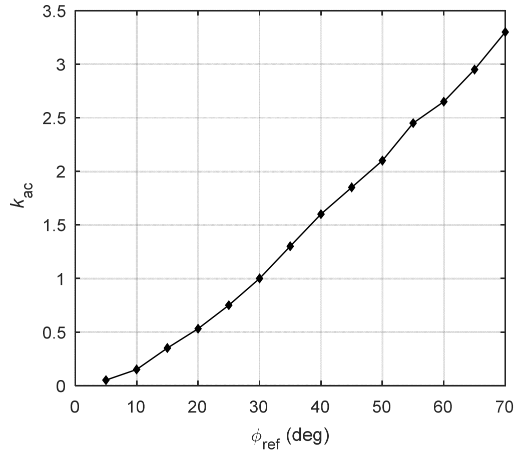

Fig.7. Dependence $k_{ac}(\varphi_{ref})$ for correction of output signal of FIS

Approximation of the obtained dependence $k_{ac}(\varphi_{ref})$ (Fig. 7) and its reproduction in a Simulink model of the positioning system with the fuzzy corrector (Fig. 1, Fig. 2) is performed utilizing feedforward artificial neural network (ANN) and back propagation training algorithm (Fig. 8).

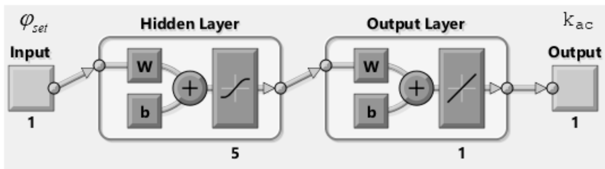

Fig.8. Structural diagram of the ANN reproducing the dependence $k_{ac}(\varphi_{ref})$

The studies of the quality of the dynamics of the positioning process utilizing the designed neuro-fuzzy corrector of the proportional PC (Fig. 2) were performed on Simulink model. The reactions $\varphi(t)$ of the positioning system starting from zero position for reference step signals 15º, 35º, 50º, and 70º being obtained utilizing the designed neuro-fuzzy PC corrector are demonstrated in Fig. 9.

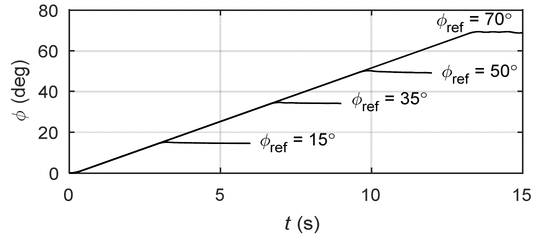

Fig.9. Reactions $\varphi_j(t)$ of a plant's position with neuro-fuzzy corrector for reference step signals 15º, 35º, 50º, and 70º

Analysis of the reactions $\varphi_j(t)$ demonstrates that the designed neuro-fuzzy corrector provides optimum laws of plant's motion (without overshoots and dragging modes) for the whole range of the reference signals for small, middle and large movements.

The plant's dynamics was found to be insensitive to the changes of load torque and inertia. Those results give reason to argue that utilizing of the proposed and designed structure of the neuro-fuzzy corrector of proportional PC allows obtaining the desired plant's dynamics in the whole range of positioning angles and under the destabilizing disturbances of the vertical positioning system.

Conclusions

1. The structure of the with the triple-loop cascade control system and with the synthesized neuro-fuzzy PC corrector has been developed for a complex nonlinear positioning EMS. It allows realizing optimum laws of motion of the plant for small, middle and large movements.

2. Fuzzy model of the correction of the output signal of the proportional PC based on the Mamdani fuzzy inference system and the feedforward artificial neural network has been designed. It allows obtaining optimum output reactions $\varphi(t)$ invariant to the positioning angle and to parametric and coordinate disturbances.

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