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TEACHING-PLAYBACK CONTROL OF ELECTRO-PNEUMATIC SERVO-DRIVE

SUMMARY

In paper a Fuzzy Logic Controller (FLC) of PD type to teaching-playback control of electro-pneumatic servo-drive are presented. The analysed fuzzy logic controller carry out a tasks: transpose control, follow-up control and teaching/play-back control. The fuzzy logic PD controller enables precise positioning of pneumatic servo-drive with the precision specified for industrial manipulators. A lot of simulation and experimental tests were carried on pneumatic servo-drive with fuzzy controller which was used for its transpose and tracking control. The designed fuzzy system is efficient, stable and resistant to disturbances and can be applied in any configurations of pneumatic servo-drive without necessity to tune the regulator, apply signal filtration or additional operations in track control or restrict the signals generated. The teaching-playback control system using fuzzy logic control was constructed and practically applied in various servo-pneumatic systems used in production automation.

Keywords: *electro-pneumatic servo-drive, teaching-playback control, fuzzy logic controller, rapid prototyping*

STEROWANIE UCZENIEM I ODTWARZANIEM SERWONAPĘDU ELEKTROPNEUMATYCZNEGO

W artykule przedstawiono regulator rozmyty typu PD do sterowania z uczeniem i odtwarzaniem serwonapędu elektropneumatycznego. Analizowany regulator rozmyty realizuje zadania: regulacji przestawnej, nadążnej oraz sterowania uczenie/odtworzenie. Regulator rozmyty PD umożliwia precyzyjne pozycjonowanie serwonapędu pneumatycznego z jakością regulacji odpowiadającą pracy przemysłowej. Przeprowadzono badania symulacyjne i eksperymentalne serwonapędu pneumatycznego dotyczące regulacji przestawnej i nadążnej. Zaprojektowany system rozmyty jest rozwiązaniem wykazującym się stabilną i odporną na zakłócenia pracą. Może być zastosowany w różnych konfiguracjach sprzętowych serwonapędu pneumatycznego bez konieczności strojenia regulatora, stosowania filtracji sygnałów oraz dodatkowych operacji w torze regulacji, np. ograniczenia pracy integratora czy ograniczenia generowanych sygnałów w porównaniu z regulatorami klasycznymi. Zaprojektowany układ sterowania z uczeniem i odtwarzaniem został praktycznie sprawdzony w systemach serwopneumatycznych i zastosowany w urządzeniach do automatyzacji produkcji.

Słowa kluczowe: *serwonapęd elektropneumatyczny, sterowanie uczenie/odtworzenie, regulator rozmyty, szybkie prototypowanie*

1. INTRODUCTION

Development of automation and robotization in manufacturing process stimulates interest in pneumatic servo-systems whose advantages include low manufacturing costs, high dynamics and reliability. Unsatisfactory positioning accuracy of multiaxis pneumatic servosytems considerably reduces their application in manipulating machines, manipulators and robots. Rapid advance in parallel pneumatic manipulators imposes a lot of demands on controllers of pneumatic servo-drive concerning positioning accuracy, resistance to alternating parameters of state and disturbing signals.The problem of positioning accuracy of servo-pneumatic systems is difficult to solve when no sufficient information on the process of conversion of the compressed gas energy into mechanical energy of pneumatic cylinder is available. Because of that, new control methods based on artificial intelligence, for example, fuzzy logic are introduced. In traditional control systems of pneumatic servo-drives control algorithms are designed intuitively on the basis of operator's experience. In fuzzy control the knowledge base rules is the result of experience, intuition as well as theoretical and practical understanding of control system dynamics which in this case is the dynamics of pneumatic servosystems. Thanks to fuzzy logic the operator's knowledge can be represented by means of mathematical operations. Fuzzy control enables moving from qualitative to quantitative control of pneumatic servo-drive. Application of fuzzy controller makes control of multiaxial pneumatic sevosystems possible in manipulators and robots of various kinematic structures: series, parallel or hybrid series/parallel (Dindorf and Takosoglu 2005).

Advancements in software for rapid prototyping in real time and in hardware-in-the-loop simulations enable to construct and test positioning fuzzy control of pneumatic servo-drives in laboratory conditions. Such an approach minimizes the design costs of control systems of pneumatic servo-drives.

2. RESEARCH STAND

The view of research stand of pneumatic servodrive motion teaching-playback control system are presented in Figure 1 and the diagram of control system are presented in Figure 2. System of additional potentiometer position transducer was expanded which is motion trajectory adjuster.

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The test stand consists of the following elements:

- pneumatic rodless cylinder (Festo DGP-25-224) with piston diameter of 25 mm and stroke length of 224 mm,
- proportional 5/3 directional control valve (Festo MPYE-5-1/8-HF-010-B) of nominal flow rate 700 l/min and switching frequency 100 Hz controlled by analog voltage signal 0–10 V,
- non-contact micropulse displacement transducer (Balluff BTL5-A11-M0600-P-S32), analog output signal – voltage 0–10 V,
- linear potentiometer (Festo MLO-POT-225-TLF), supply voltage 13–30 V, output voltage 0–10 V, resistance 5 kΩ, frequency 5 Hz–2 kHz,
- 16-bit measurement card (Measurement Computing Corporation AD/DA PCI-DAS1602/16) with 8 inputs and 2 analog outputs,
- PC computers Host and Target.

The proposed distributed measurements and control systems based upon two PC computers Host and Target is shown on the Figure 3. The distributed system was used for rapid prototyping of fluid power servo-drives (electro hydraulic and pneumatic servo-drives) in real time (Dindorf 2008). On PC computes Matlab-Simulink and *xPC Target* were installed. In Matlab-Simulink package it is possible to create processing procedures for both conventional and artificial intelligence controllers and to execute own control and visualization applications. PC has the card of analog input/output and *Real-Time xPC Target* system which is used for measurement data acquisition and fluid power drives control.

Target PC can simulate the flow of control and measurement signals in real time by means of HIL (*Hardware-in--the-Loop*) method. Applications run by Si-mulink model use a real time kernel of the PC computer.

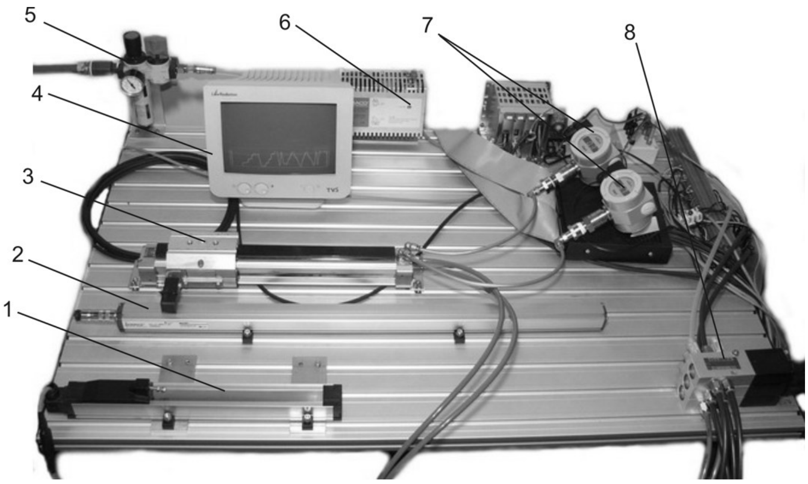

Fig. 1. General view of the research stand of electro-pneumatic servo-drive single axis teaching-playback control system: 1 – potentiometer position transducer (motion trajectory adjuster), 2 – magnetostriction position transducer, 3 – rodless cylinder, 4 – xPC Target computer screen, 5 – pneumatic FR unit, 6 – power supply, 7 – pressure transducer, 8 – servo-valve

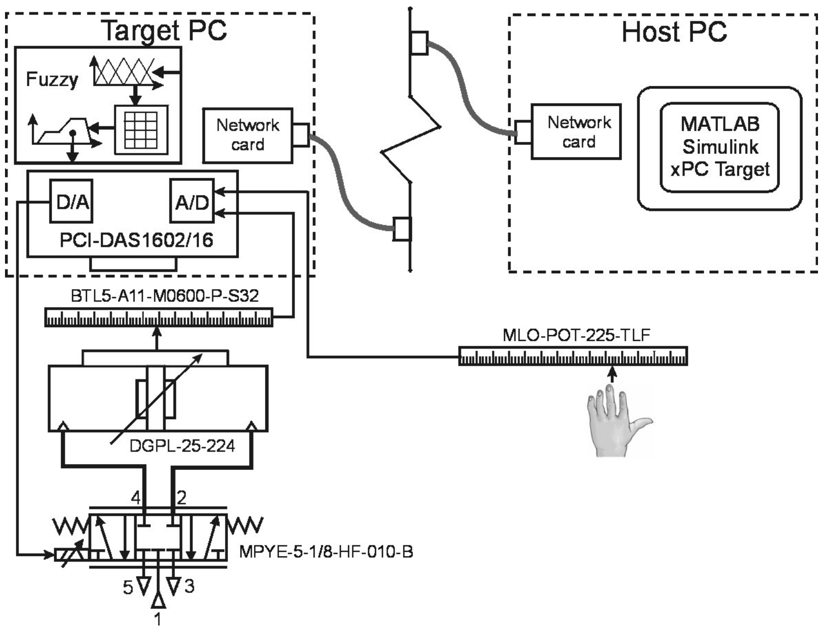

Fig. 2. The diagram of electro-pneumatic servo-drive teaching-playback control system

Host PC and Target PC communicate with each other by TCP/I protocol. The communication of supervisory control layer in Host PC with direct control layer in Target PC may occur continuously, periodically or at operator's specified time intervals. The software suite used in Host PC and Target PC and connections between the two computers are shown on Figure 2. Working with the rapid prototyping suite consists in building a model of the control algorithm in Simulink. Next the model is compiled and sent to the Target PC which serves as the controller of fluid power drives together with the input/output card and the *Real-Time xPC Target* system. Measurement sensors and transducers are attached to the Target PC through the measurement card. Thanks to *xPC Traget Spy* software the visiualization of the processed data and the analysis of the process of controlling fluid power drives is possible.

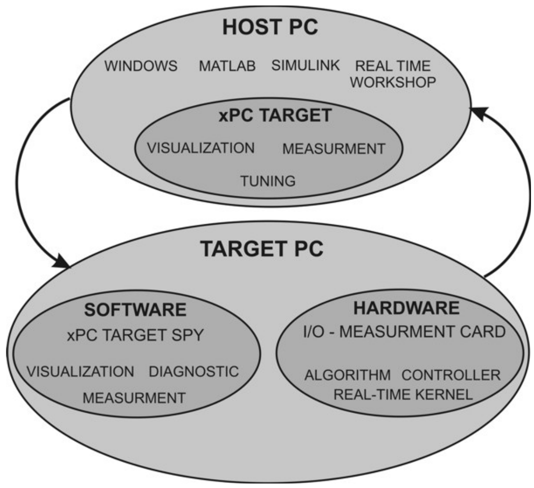

Fig. 3. Diagram of Host PC and Target PC connections (Matlab/Simulink)

3. FUZZY LOGIC CONTROLLER

The model of pneumatic servo-drive was implemented for Matlab-Simulink package with Fuzzy Logic Toolbox. Fuzzy PD controller constructed in Fuzzy Logic Tollbox of Matlab Simulink package was suggested for the purpose of controlling pneumatic servo-drive. The pneumatic servo-drive together with fuzzy PD controller constitute a system of MISO type with two inputs: position error $e(t)$ and change of position error $\Delta e(t)$ and one output: proportional valve coil voltage $u(t)$. Output and input signals underwent fuzzification process with regular distribution of 7 fuzzy sets of triangular and trapezoid membership functions) (Takosoglu and Dindorf 2005). The knowledge base rules of fuzzy controller are 49 Mac Vicar-Whelen rules described in the table entered to Fuzzy Logic Toolbox. In the inference process the firing degree was determined by means of MIN operator, implication operator and all the inputs of particular rules were aggregated by MAX operator. In the defuzzy-fication process the center-of-gravity-method (COG) was applied. The dialogue window "Rule Viewer" of Fuzzy Logic Toolbox is a kind of diagnostic device which enables tracing which fuzzy rules were activated on particular states of input. It also enables observation of fuzzy system output value. The fuzzy logic controller of PD type was tuned by means of Simulink Response Optimization Toolbox of Matlab-Simulink package. The controller had two inputs $e(t)$ – position error and $\Delta e(t)$ – change of position error and one output $u(t)$ –voltage of coil valve obtained by means of Fuzzy Logic Toolbox of Matlab-Simulink package. The fuzzy controller operates on knowledge base containing IF-THEN rules for undetermined predicates and fuzzy control mechanism (Driankov *et al.* 1996):

$$u(k) = F\left[e(k), e(k-1), ..., e(k-v), u(k-1), u(k-2), ..., u(k-v)\right] \tag{1}$$

where:

- $u(k)$ – control signal describing relation between controller's input and output,
- $e(k)$ – position error between input signal $y_0(k)$ and output signal $y(k)$,
- k – discrete time (sampling instant), $k = t/T$,
- t – continuous time,
- T – sampling period,
- v – parameter determining controller's order,
- F – nonlinear function describing knowledge base rules of FLC.

The FLC Controller describes relations between the change of control signal) $\Delta u(k)$ from one side and position error $e(k)$ and change of position error $\Delta e(k) = e(k) - e(k-1)$ from the other side. Thus fuzzy logic control relation for $v = 1$ can be written as follows:

$$u(k) = F\left[e(k), \Delta e(k)\right] \tag{2}$$

The real output of $u(k)$ controller is obtained from the past control value $u(k-1)$ and its updating $\Delta u(k)$ as follows:

$$u(k) = u(k-1) + \Delta u(k) \tag{3}$$

The fuzzy controller of this type was proposed for the first time by Mamdan and Assilian, and was called fuzzy logic controller of Mamdani type (Yager and Filev 1994). The inference algorithm transforms the Control Law into non-fuzzy control algorithm which resembles the equation of traditional PD controller):

$$u(k) = k_P \cdot e(k) + k_D \cdot \frac{\Delta e(k)}{T} = k_P \cdot e_P(k) + k_D \cdot e_D(k) \tag{4}$$

where k_P and k_D represent proportional gain and derivative coefficient of the controller.

The rules for fuzzy PD controller are written as follows:

IF $e_P(k)$ is <linguistic label> AND $e_D(k)$ is <linguistic label> **THEN** $u(k)$ <linguistic label>.

The position error $e(k)$ changed in the range from –3,7 V to 3,7 V which was the range of displacement of slide cylinder. For extreme values Γ and L sets were used which enabled to compensate the incomplete knowledge base for high amplitude values of $e(k)$ signal. Additionally, for position error $e(k)$ approaching zero a set of trapezoid type was used which enabled to determine the value of the assumed static error 2δ and to avoid oscillation around the zero error. For $\Delta e(k)$ signal the domain was determined in the range from –25 V/s to 25 V/s which corresponded to the range of displacement of slide cylinder. With the above assumptions taken into account the input signal $e(t)$ underwent fuzzyfication process with distribution of fuzzy sets (Fig. 4) while the input signal $\Delta e(t)$ underwent defuzzyfication process with distribution of fuzzy sets (Fig. 5). The measurements showed that flow rate characteristics of the proportional control valve are asymmetrical. Therefore, in the central position of spool valve where the voltage was 5 V the set of sigmoidal type shifted towards right (in accordance with the asymmetrical character of the valve) was used. For extreme fuzzy sets the sets of Γ and L type were applied as it was the case for input signals. In Figure 6 the fuzzyfication process of input variable $u(t)$ is presented. Knowledge base rules contained 25 fuzzy rules included in Table 1. As the number of fuzzy rules and consequently the number of fuzzy sets was limited to 25 the sets were concentrated/refined near zero error. This enabled smooth change of output signal near zero error, which implies, small jumps of the signal while passing from one fuzzy rule to the other. Twenty five FLC's knowledge base rules (Tab. 1) forming FLC's control surface are presented in Figure 7. In the fuzzy inference process the firing degree of MIN type, fuzzy implication of MIN type and aggregation of particular outputs of the rule of MAX type were determined. In order to obtain crisp value the method of the Centre of Gravity was used.

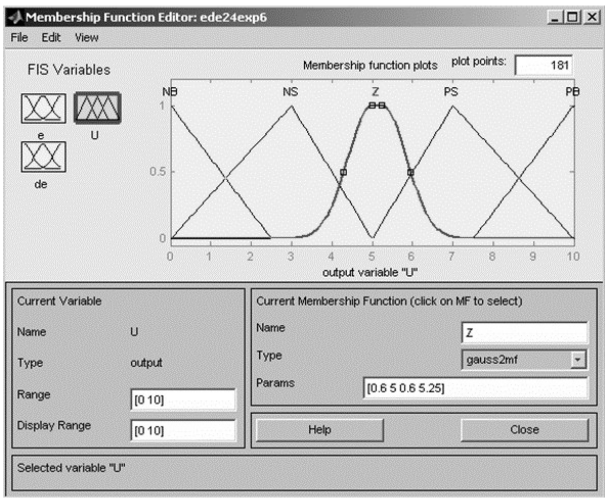

Fig. 4. Membership functions for the input $e(t)$

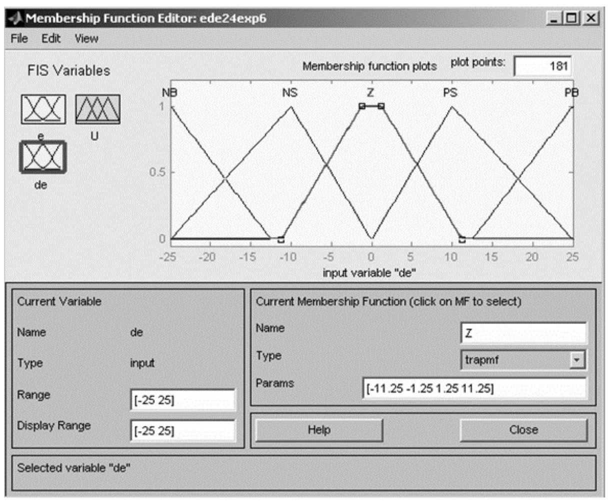

Fig. 6. Membership functions for the output $u(t)$

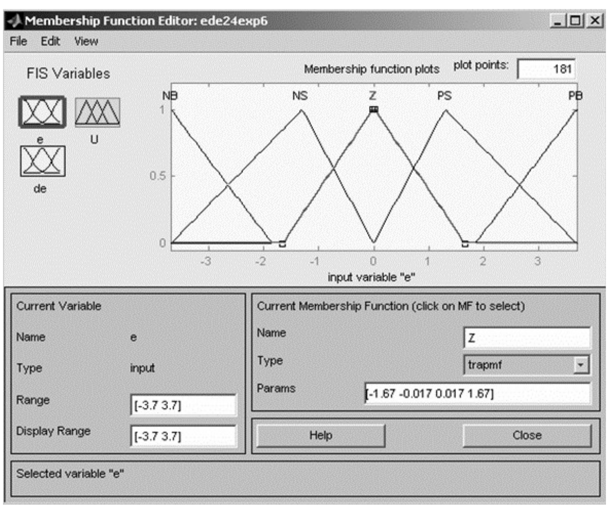

Fig. 5. Membership functions for the input $\Delta e(t)$

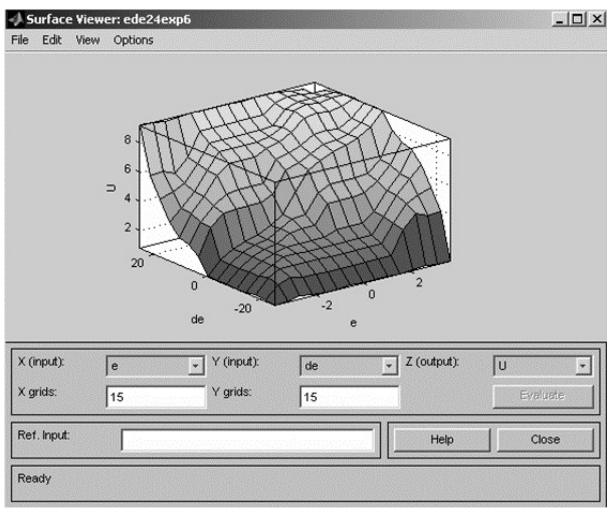

Fig. 7. Output control surface

Table 1

Knowledge base – relative matrix with rules

Δe\e	NB	NS	Z	PS	PB
NB	NB	NB	NB	NB	NB
NS	NB	NS	NS	NS	PS
Z	NB	NS	Z	PS	PB
PS	NS	PS	PS	PB	PB
PB	PB	PB	PB	PB	PB

4. RESULTS OF EXPERIMENTAL TESTS

Its input signal introduced manually by the operator by means of linear potentiometer was reproduced by pneumatic cylinder of pneumatic servo drive. In the teaching-play-back control system the software with PD Fuzzy PD Controller performing the task of teaching the pneumatic servo-drive motion was used (Takosoglu and Dindorf 2007). The suggested control system operates as follows: the operator by manually moving the linear potentiometer sets an optional motion trajectory and next the slide of rodless cylinder of pneumatic servo-drive reproduces this trajectory in real time. During the experimental tests optional motion trajectories were set by means of linear potentiometer and motion trajectories reproduced by pneumatic servo-drive were recorded in real time. Each trajectory could be reproduced unlimited number of times in real time or recorded in the control program. The recorded motion trajectories were then reproduced by pneumatic servo-drive. The quality of teaching/play-back control with FLC Controller was checked by means of standard performance indexes including position error $\delta_x = |x_0 - x(t)|$, velocity error $\delta_v = |v_0 - v(t)|$ and acceleration error $\delta_a = |a_0 - a(t)|$. In follow-up control the additional quality criteria comprised: absolute error signal $\Delta x(t)$ of velocity $\Delta v(t)$ and acceleration position $\Delta a(t)$ (Takosoglu *at al.* 2008):

$$\Delta x(t) = \frac{\sum_{i=1}^{N} |x_0(i) - x(i)|}{N} \tag{5}$$

$$\Delta v(t) = \frac{\sum_{i=1}^{N} |v_0(i) - v(i)|}{N} \tag{6}$$

$$\Delta a(t) = \frac{\sum_{i=1}^{N} |a_0(i) - a(i)|}{N} \tag{7}$$

where:

$x(t)$ – position,
$v(t)$ – velocity,
$a(t)$ – acceleration,
N – number of measuring points.

The results of experimental tests on displacement, position error, velocity and velocity error as well as acceleration and acceleration error of cylinder slide of pneumatic servo-drive during playback of optional motion trajectory are presented in Figure 8. The changes of absolute follow-up error

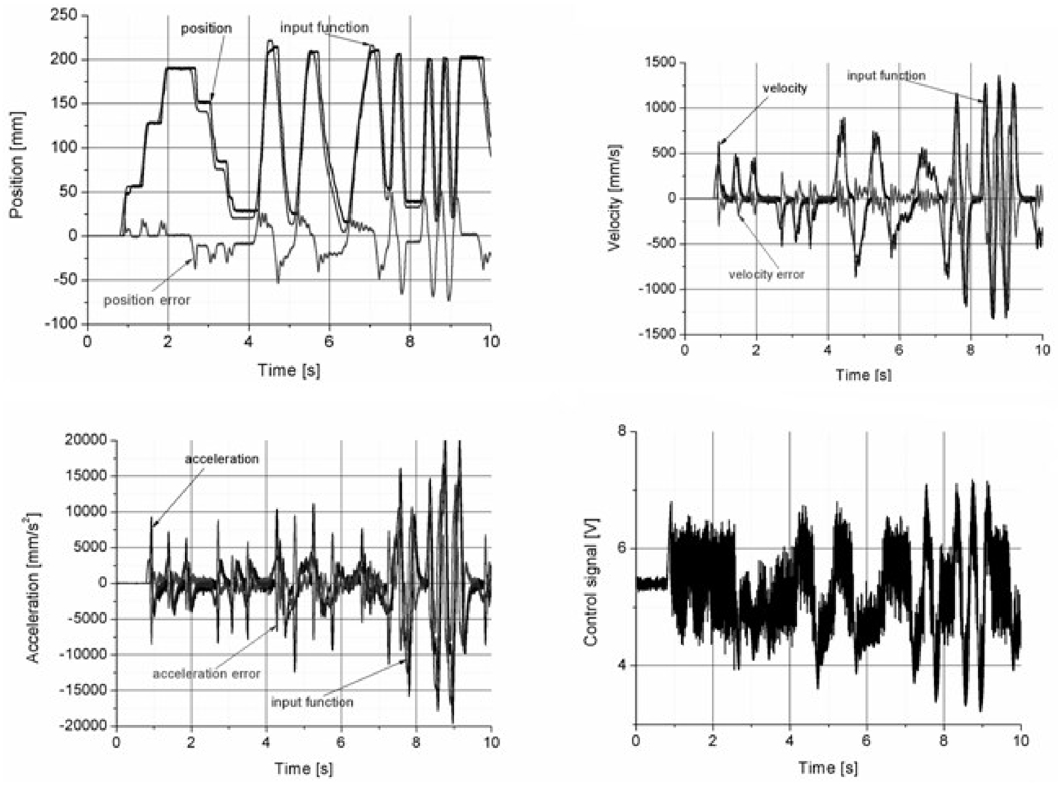

Fig. 8. Experimental results of position *x*, velocity *v*, acceleration *a* of pneumatic cylinder slide and control signal in proportional valve

signal of displacement, velocity and acceleration of pneumatic servo-drive cylinder slide are presented in Figure 9. Pneumatic servo-drives with teaching-playback control system have considerable practical significance, especially in the control of manipulating machines, manipulators, industrial robots as well as rehabilitation and physiotherapy manipulators. The proposed teaching-playback control of pneumatic servo-drive motion was applied in production automation, for example, to transfer and segregate all kinds of details of untypical dimensions and shapes.

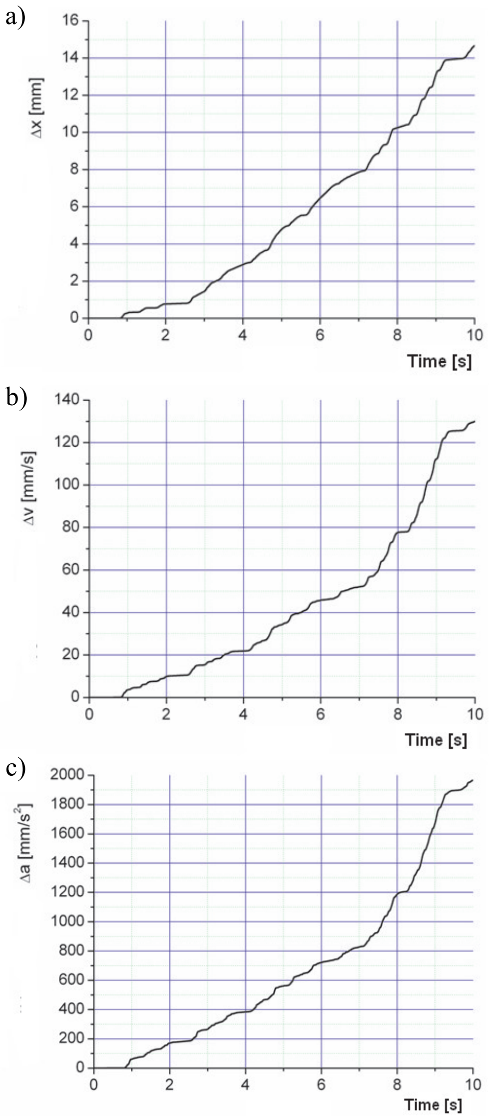

Fig. 9. Experimental values of absolute follow-up error signal of position Δx (a), velocity Δv (b) and acceleration Δa (c)

5. CONCLUSION

In paper a Fuzzy Logic Controller of PD type to positioning control and teaching-playback control of electro-pneumatic servo-drive are presented. The fuzzy logic PD controller enables precise positioning of pneumatic servo-drive with the precision specified for industrial manipulators. A lot of simulation and experimental tests were carried on pneumatic servo-drive with fuzzy controller which was used for its transpose and track control. The designed fuzzy system is efficient, stable and resistant to disturbances and can be applied in any configurations of pneumatic servo-drive without necessity to tune the regulator, apply signal filtration or additional operations in track control or restrict the signals generated. The teaching-playback control system using fuzzy logic control was constructed and practically applied in various servo-pneumatic systems used in production automation. The designed fuzzy system processes a measurement data every 0,5 ms that is 2000 Hz. By comparison with a industrial controller, FLC haven't a restrict the time and number of measurement data and a measurement in real time.

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