Design Rules for Fuzzy Logic Controllers for Pneumatic Systems

Jakub Takosoglu(✉), Ryszard Dindorf, and Piotr Wos

Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Al. Tysiaclecia Panstwa Polskiego 7, 25-314 Kielce, Poland
qba@tu.kielce.pl

Abstract. Position control is particularly important in systems with pneumatic drives. Many centres around the world are looking for an optimal and effective method especially for rod and rodless pneumatic cylinders. Position control of pneumatic drives is a difficult process due to the compressibility of the working medium, friction occurring in the drive system, stick-slip phenomenon, clearances in the cylinder, sticking of the piston to the cylinder in final positions. The problem is to set and maintain a constant speed of motion, especially in the low speed range, and to precisely stop the piston of the cylinder in intermediate positions between the end positions of the cylinder.

The article presents the theoretical foundations of fuzzy logic controllers and the principles of their design for pneumatic drive systems. A fuzzy control system for an electro-pneumatic servo-drive made of a rodless cylinder controlled by a proportional flow valve has been analysed. An experimental stand for testing designed fuzzy logic controllers and assessing the quality of control has been presented. Experimental tests have been conducted for the implementation of changeover control, tracking control and following up the curvilinear trajectory.

Keywords: Fuzzy logic controller · Electro-Pneumatic Servo-Drive

1 Introduction

Problems related to the optimal control of pneumatic devices contributed to the search for new AI-based control techniques methods – fuzzy logic [1]. Use of FLC fuzzy logic controllers enables the transition from a quantitative description to a qualitative description of the process [2]. In traditional control systems, control algorithms are developed intuitively by operators based on their own experience. Applying fuzzy logic methods, knowledge gained during process operation and handling, or the knowledge of operators, i.e. intuitive algorithms for controlling control objects, can be saved with verbal logic converted into mathematical operation and used in the control process. Fuzzy logic systems can also be used in processes where there are non-linearities, uncertainties about their parameters or other adverse features of a control object. Fuzzy logic systems are intelligent control methods [3–5] in which the knowledge encoded in the rule base

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results from experience and intuition as well as theoretical and practical understanding of process dynamics [5, 6]. The use of fuzzy logic in controllers results from the fact that the knowledge of the process dynamics is not required for the correct tuning of the controller. Fuzzy control is also popular because the actual control objects are non-linear and therefore require special control techniques, which are usually very difficult, laborious and sometimes impossible to design. For such objects, designing fuzzy controllers can be much easier, and they can replace standard or status controllers [7].

2 Fuzzy Logic Controllers

The fuzzy control algorithm is a knowledge-based algorithm, described by fuzzy logic methods [8]. Fuzzy control systems are some kind of expert systems based on knowledge. The knowledge base contains a control algorithm stored as a rule base. The control strategy and knowledge contained in the rule base are derived from human experience and intuition and from a theoretical and practical understanding of the dynamics of a controlled object. The main difference between conceptually fuzzy and conventional control is the lack of analytical description [8].

The Control Law (1) of the fuzzy controller is described by a knowledge-based system containing ***IF-THEN*** rules with unspecified predicates and a control mechanism with fuzzy logic [8]:

$$u(k) = F[e(k), e(k-1), \ldots, e(k-v), u(k-1), u(k-2), \ldots, u(k-v)] \quad (1)$$

where F is a non-linear function representing the FLC fuzzy controller described by the rule base. The FLC describes the relationship between the *u(k)* control signal on the one hand and the *e(k)* error and its change $\Delta e(k)$ on the other. Therefore, the overall relationship of the FLC control (2) for v = *1* can be presented as follows:

$$u(k) = F[e(k), \Delta e(k)] \quad (2)$$

In the case of a fuzzy logic controller, its type – P, PI, PD, PID – determines the selection of process status variables, control variables and the content of the predecessor and successor of each rule. For process status variables (input variables) that represent the rule predecessor content, i.e. the ***IF*** rule part, the following is obtained:

- control error e,
- control error change Δe,
- control error sum δe,

For process control variables (output variables) that represent the rule predecessor content, i.e. the ***THEN*** rule part, the following is obtained:

- for-loop u,
- for-loop change Δu.

By analogy to the standard controller, it can be presented as follows:

$$
\begin{aligned}
e(k) &= y_0(k) - y(k) \\
\Delta e(k) &= e(k) - e(k-1) \\
\Delta(\Delta e(k)) &= e(k) - 2e(k-1) + e(k-2) \\
\delta e(k) &= \sum_{i=1}^{k} e(i) \\
\Delta u(k) &= u(k) - u(k-1)
\end{aligned}
\tag{3}
$$

where:
$y_0(k)$ – set-point (input function),
$y(k)$ – command (response).

PID fuzzy logic controllers PID implemented in two versions: direct and incremental (see Fig. 1).

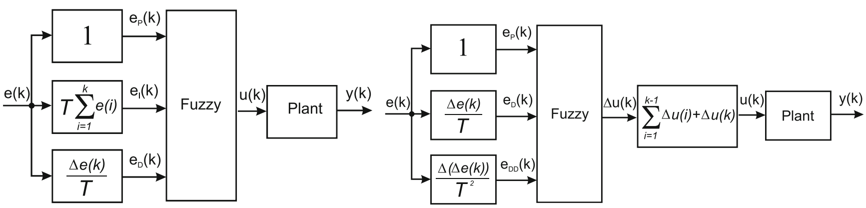

Fig. 1. Direct and incremental version of the PID fuzzy logic controller.

In the direct version, the control signal *u(k)* is calculated at any time, while the control signal change value $\Delta u(k)$ is calculated in the incremental version. To calculate the control variable value *u(k)*, an additional controller block, the so-called adder, is required. The incremental version of the controller is more sensitive to measurement noise, therefore the experimental tests presented below will be performed only on the basis of the direct version.

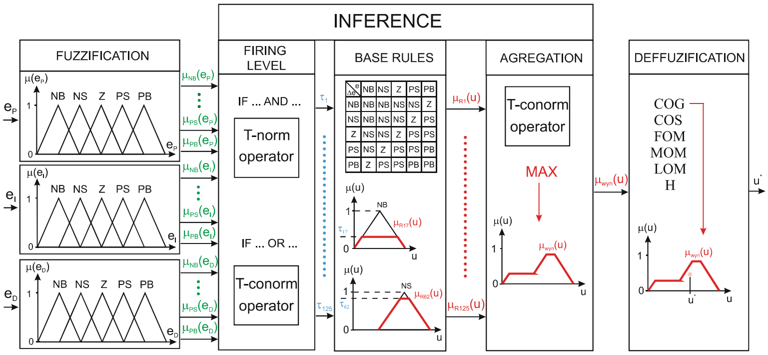

Fig. 2. Fuzzy structure.

The structure of the fuzzy part for the direct version is shown in Fig. 2. Five main stages of fuzzy inference were taken into account (fuzzification, determination of rule firing levels, launching of rules, aggregation of individual rule outputs, defuzzification).

Due to the complexity of the fuzzy inference process, the structure of the fuzzy part presented in Fig. 2 contains only some of the results of the full process. Fuzzification was carried out in three e_P, e_I, e_D tracks using seven fuzzy sets of NB, NM, NS, Z, PS, PM, PB. The firing level, depending on the design of the premise in the rule base, can be determined using T-norm or T-conormy operators. The complete rule base contains 147 rules including all combinations of NB, NM, NS, Z, PS, PM, PB inputs. The launching of rules was performed using the Mamdani implication and the aggregation of the fuzzy sets $\mu_{Ri}(u)$ of launched rules using the *MAX* T-conormy operator. Defuzzification was performed using the COG (Center of Gravity) method.

2.1 Design Rules for Fuzzy Logic Controllers

Due to the complexity of fuzzy logic instrument, designing FLC fuzzy controllers can be a complex and time consuming process. The problem is both the determination of the FLC parameters, i.e. the linguistic labels and fuzzy sets, and the structure of the FLC – rule base with a fuzzy inference mechanism. To perform the fuzzy operation, the membership function must be precisely defined in terms of quantity, i.e. parameters and function coefficients, as well as quality, i.e. function types.

The following rules are recommended for determining parameters and tuning fuzzy logic controllers [9]:

- The most commonly used membership functions are triangular functions,
- number of intersection points of two membership functions – the intersection coefficient usually takes the value of 1 (one intersection point),
- the membership function value at the intersection point of the membership function – the intersection level usually assumes the value 0.5,
- symmetrical membership functions are most often applied,
- A large range of cut-off values in the membership function diagram means low gain, and narrow membership functions mean high sensitivity of the controller,

- The fuzzy logic controller can be tuned by changing the shape of the membership function.

Building a rule base is the most difficult stage of designing fuzzy logic controllers. It is also a cause for criticism of fuzzy logic control because, in principle, there are no systematic tools to create a FLC rule base [8].

The fuzzy control algorithm reflects the control mechanism implemented by people, without the use of any formalised knowledge of the controlled object in the form of mathematical models and without the analytical description of the control algorithm [8]. One way to derive a linguistic control strategy is human experience and reasoning, another way is to observe the phase surfaces of conventional PI, PD, PID controllers, from which fuzzy logic control rules can be derived.

Another, more formal approach to FLC rule base construction is to use a template rule base. The template rule base can be considered a basic tool that combines engineering common sense and fuzzy logic control experience [8]. This standard rule base is the one proposed by Mac Vicar-Whelan (Table 1).

Table 1. Mac Vicar-Whelan rule base.

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

Knowledge of the technical and operational parameters of pneumatic control elements is extremely important when designing control systems. Manufacturers usually give only basic parameters of their products and also present selected theoretical characteristics. Such ideal characteristics can introduce errors into the control system. Position control of pneumatic drives uses proportional valves for pressure and flow. Pneumatic proportional valves (servo-valves) are elements with a high gain of the input signal. They are used to amplify and transform continuously a weak input signal into a strong output signal in the form of flow rate (flow valves) or pressure (pressure valves). The highest gain can be achieved by using electrical signals as input signals, thus proportional valves with electrical control are most often applied. The valve consists of two basic units:

- An electromechanical transducer that converts an electrical voltage or current signal into either linear (angular) motion or force (moment),
- one-, two-, or three-stage amplifier, and
- spool valve.

Proportional valves are used primarily in control systems for fast-changing production processes. The design of electro-pneumatic servo-valves does not differ significantly from electrohydraulic servo-valves. Most often, these are slide servo-valves with four or two distributing edges. Pneumatic servo-valve slide-sleeve assemblies do not contain elastic seals to reduce frictional resistance and the resulting hysteresis. The lack of sealing is a source of significant compressed air leakage, which is prevented by the use of a positive cover of the flow channels in the slider-sleeve assembly, which, however, introduces a servo-valve insensitivity zone in the middle position of the slide. Knowledge of the actual characteristics of the control valve can significantly facilitate the design process of the fuzzy logic controller for the electro-pneumatic servo-drive, as fuzzy logic provides the opportunity to eliminate non-linear phenomena occurring during the control process.

3 Object of Study

The experimental tests focused mainly on the design and implementation of the fuzzy control algorithm for the electro-pneumatic servo-drive for the task of precise positioning (changeover control, tracking control and any motion trajectory). In industrial environments, servo-drives are performing increasingly complex positioning tasks under changing operating conditions [10]. Due to the increasing demands on pneumatic servo drives, the control algorithm must be resistant to variable mass load [11], change of the set piston motion speed of the cylinder, change of the set piston position of the cylinder, change of the frequency of the set sinusoidal trajectory, change of the supply pressure, to the type and accuracy of the applied position transducers, to the parameters of the pneumatic cylinder used for construction. Figure 3 shows a diagram of an electro-pneumatic servo drive, in which a rodless cylinder is used as an actuator.

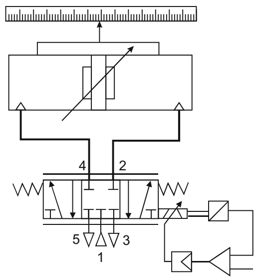

Fig. 3. Electro-pneumatic servo-drive diagram with rodless cylinder.

The main components of the servo drive are:

- DGPL-25-224 rodless cylinder from Festo (Fig. 4a),
- MPYE-5-1/8-HF-010-B proportional valve from Festo (Fig. 4b),
- BTL5-A11-M0600-P-S32 magnetostriction transducer of Balluff (Fig. 4c).

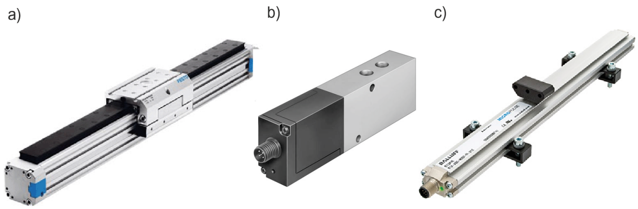

Fig. 4. General view: a) rodless cylinder, b) proportional valve c) magnetostriction transducer.

MPYE-5-1/8-HF-010-B proportional valve is a five-way, three-position, voltage controlled valve (0 ÷ 10 V). It is a valve with a nominal flow rate of 700 l/min and a switching time of 80 Hz [12]. Figure 5a shows the actual flow characteristics [13] of the valve and Fig. 5b shows the actual pressure characteristics of the valve.

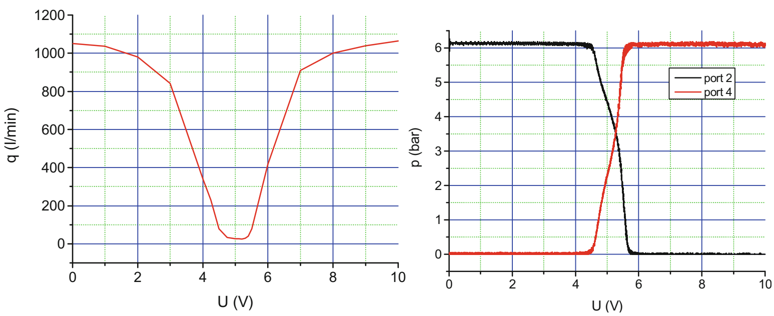

Fig. 5. Pressure and flow characteristics.

A rodless cylinder 224 mm long and a piston diameter of 25 mm was used as the drive. A non-contact magnetostrictive position transducer with a gauge length of 600 mm and resolution of less than 2 μm with an analogue output (0 ÷ 10 V) works basing on the magnetostrictive effect principle. Figure 6 shows the measurement noise of the magnetostrictive position transmitter.

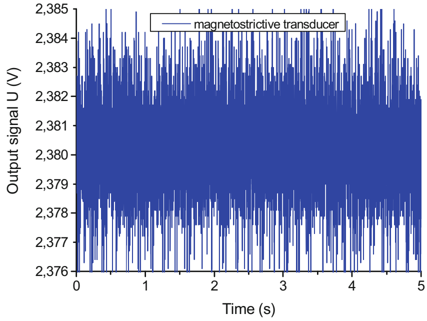

Fig. 6. Measurement noise of the BTL5-A11-M0600-P-S32 position transducer.

4 Fuzzy PD Controller Design

When designing the PD fuzzy logic controller, experimental tests of the proportional valve and the position transducer were taken into account. The controller was designed using the *Fuzzy Logic* toolbox of Matlab-Simulink package. The variable domain error e is defined from -3.7 V to 3.7 V because these values correspond to the operating range of this variable for the DGPL-25-224 rodless cylinder with BTL5-A11-M0600-P-S32 position measurement. The Γ and L-type sets are used for extreme values, which avoids the lack of completeness of the knowledge base for large amplitude values of the error e input signal. In addition, a trapezoid set was used for the near zero error to determine the value of the assumed static deviation 2δ and to avoid oscillations around the near zero deviation and the set was compacted. This reduced the dynamics of the system but allowed achieving "smoothness" of the output signal (i.e. small jumps when passing from one rule to another) near the zero error. For the second input signal, i.e. the change of error Δe, the same was done during the fuzzy process, but its domain was set from $-$ 25 V/s to 25 V/s, because these values of the amplitude of the input signal Δe correspond to the maximum speed of error change (maximum speed of the cylinder). Taking into account the above mentioned assumptions, the input signal of the e error was subjected to the fuzzy process with the distribution of fuzzy sets as in Fig. 7a, while the input signal Δe as in Fig. 7b.

For the magnetostrictive transducer the measurement noise is ± 0.007 V. The determination of the measurement noise was necessary to determine the assumed static deviation and thus to calculate the quality indicators for the control of the fuzzy electro-pneumatic servo drive. The determination of the measurement noise was also used to correctly design the fuzzy logic controller. Due to the position transducer used and the requirements for pneumatic drives under industrial operating conditions, a static deviation $2\delta = \pm 0.022$ V was assumed.

As experimental tests (flow characteristics) have shown, the proportional valve from Festo does not operate symmetrically and the flow curve is similar to the sigmoid shape. Therefore, a sigmoid fuzzy sets shifted to the right (due to the asymmetrical operation of the valve) were used. For extreme fuzzy sets Γ and L-type sets are used, similarly to input signals. The rule base comprises of 49 fuzzy rules presented in Table 1.

5 Experimental Tests

The experimental tests on the electro-pneumatic servo-drive were mainly focused on checking the operation of the PD fuzzy logic controller under changing operating conditions. The fuzzy logic controller had a feedback loop from the position of the cylinder piston using a position transducer. Figure 7 shows a general view of the experimental test stand.

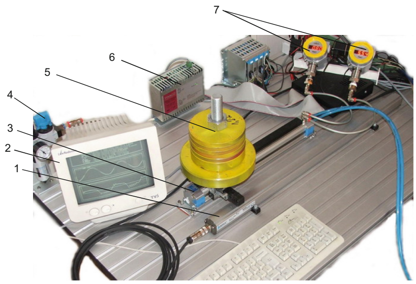

Fig. 7. A general view of the test stand: 1 – position transducer, 2 – screen, 3 – rodless cylinder, 4 – FRL unit, 5 – mass load, 6 – power supply, 7 – pressure transducer.

The problem of pneumatic servo drive positioning results from the complex and complicated process of converting the energy of compressed gas into mechanical energy of the cylinder piston motion. Solving such a problem in an environment of insufficient and incomplete information is a difficult task, but especially important when it comes to the possibility of using the proposed solution in industrial working conditions. The design of servo drives equipped with extra sensors, e.g. pressure transducers or force sensors, is uneconomic under industrial conditions. In the time of rapid development of automation and the growing demands from industrial sectors, the controller faces a number of tasks, mainly concerning the task of changeover control, tracking control and reproduction of any motion trajectories. Due to the use of pneumatic servo drives in the construction of manipulators and industrial robots, one of the most important requirements is the resistance of the control algorithm to alternating mass load and supply pressure fluctuations. Positioning is also required over a wide range of displacements and pre-set piston speeds of the cylinder.

A number of experimental tests have been conducted on the designed and built stand. The graphs below show selected dynamic and quality characteristics (IAE - Integral of Absolute Error, ISC - Integral of Square Control Signal) of electro-pneumatic servo drive piston positioning (Figs. 8, 9, 10, 11 and 12).

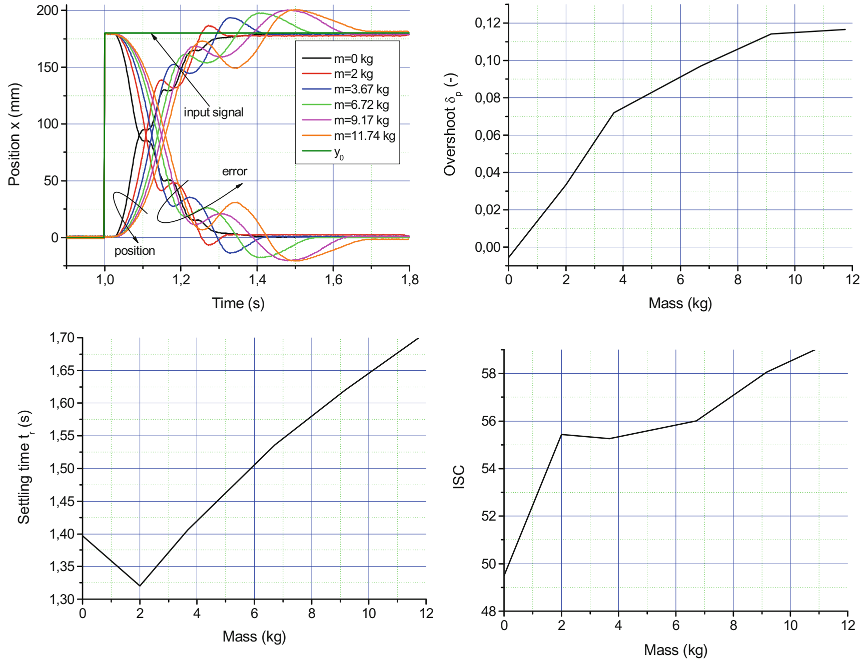

Fig. 8. Changeover control with variable load mass.

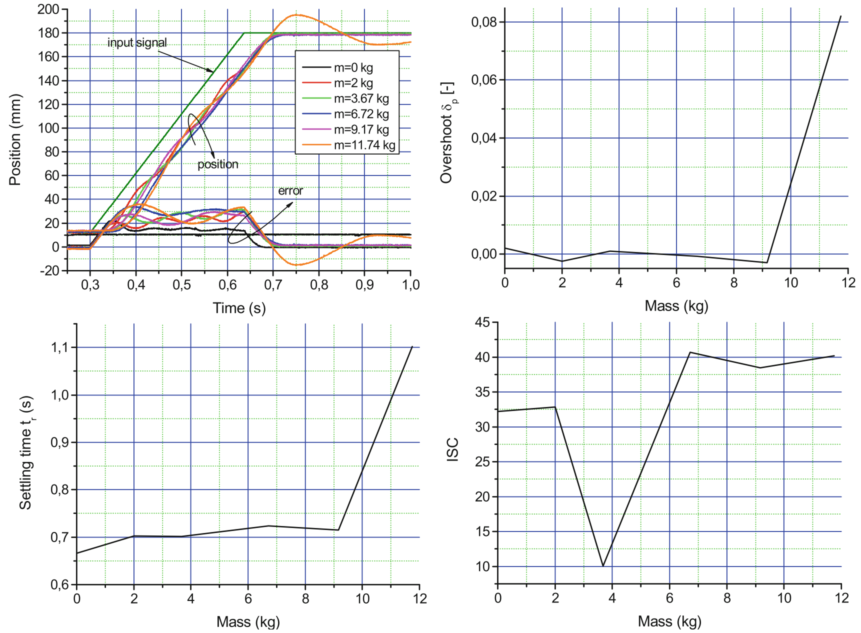

Fig. 9. Tracking control with variable load mass

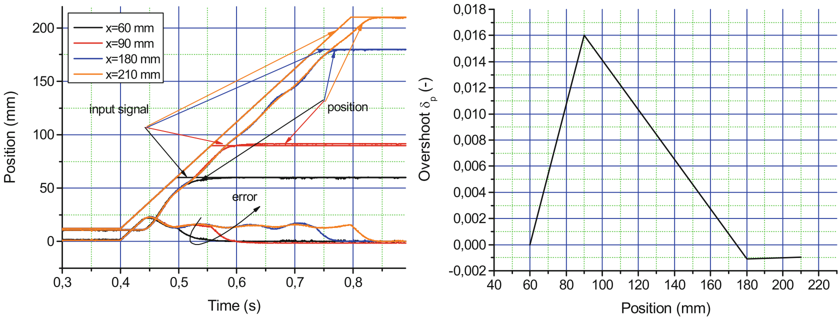

Fig. 10. Tracking control with position variable.

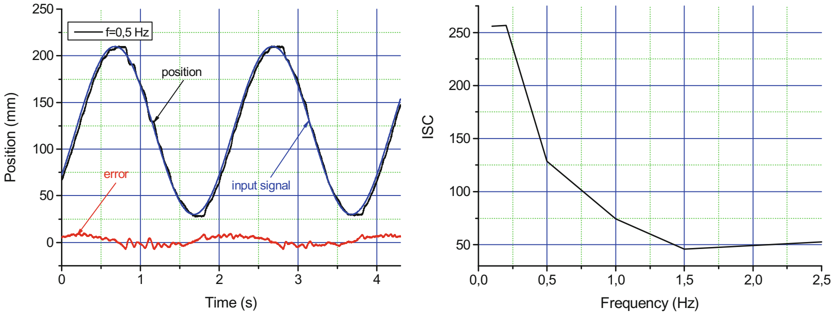

Fig. 11. Implementation of sinusoidal trajectory.

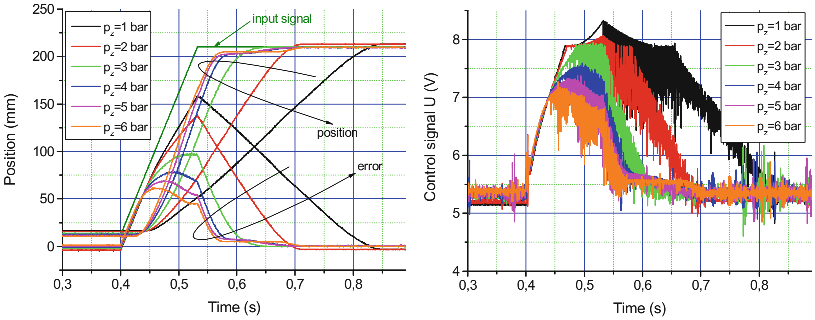

Fig. 12. Tracking with supply pressure variable.

6 Summary

Fuzzy logic controllers can be successfully applied in processes where there are nonlinearities, uncertainties about their parameters or other unfavorable features of a control object. Such features are characterized by systems with pneumatic drives and especially analyzed electro-pneumatic servo drive with a rodless cylinder controlled by a proportional flow valve. The tests have been conducted in a wide range of variable operating conditions of the servo drive. The designed PD fuzzy logic controller performed very well the assumed tasks of the changeover control, tracking control and sinusoidal trajectory. The static deviation of $2\delta = \pm 1.32$ mm has been assumed for the tests, which was a result of the measurement noise occurring in the control system and positioning accuracy required in industrial conditions. The aim of the tests was to check the resistance of the fuzzy electro-pneumatic servo control algorithm to variable mass load of the cylinder, change of the pre-set speed of the cylinder piston motion, change of the pre-set position of the cylinder piston, change of the supply pressure, change of the pre-set frequency of the sinusoidal trajectory.

The designed fuzzy logic controller is resistant to variable mass load of the cylinder. The fuzzy logic controller works correctly up to a mass of 6.72 kg in the case of the changeover control and 0.5 m/s in the case of the tracking control up to a mass of 9.17 kg.

For low speeds (0.075 m/s and 0.25 m/s), an oscillating stick-slip (transition phase from solid to fluid friction) can be observed in the initial start-up phase. Above 0.25 m/s, no stick-slip occurs. A step change in the friction force value during this phase results in a significant speed error, which is effectively compensated by the fuzzy logic controller during the further control process. The drive maintains the set point values for motion parameters. An additional advantage is that it is not necessary to tune the controller during changes in operating conditions.

The analysis of the quality characteristics showed that the piston positioning of the cylinder is accurate enough for industrial conditions.

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