Journal of KONES Powertrain and Transport, Vol. 18, No. 2 2011

PRESSURE CONTROL IN AIR CUSHIONS OF THE MOBILE PLATFORM

Edward Lisowski, Grzegorz Filo

Cracow University of Technology
Department of Mechanical Engineering
Jana Pawła II Street 37, 31-864 Kraków, Poland
tel.: +48 12 3743351, .+48 12 3743335, fax: +48 12 3748267
e-mail: lisowski@mech.pk.edu.pl, filo@mech.pk.edu.pl

Abstract

In the industrial indoor transport various devices are used. Recently, the means of transport which use air cushions are more and more popular. Air cushions are particularly useful for transporting heavy loads and devices over the hardened, smooth floor. The air cushions can be directly put under the load. Then, the load is raised of the small height and displaced. The friction force between air cushion and the floor is very small. Therefore, the load can be moved by the operator. The other case of using air cushions in industrial transport is mobile platform with suitable number of air cushions instead of wheels. One of the most important problems in this case is adjustment of the transportation force in individual air cushion. An automatic control system of the transportation force has been proposed in this work. A mobile platform with four air cushions was considered. The pressure in each air cushion was regulated separately in the feedback loop. Two types of control algorithms have been investigated: the standard PID controller as well as the fuzzy logic controller. The investigations contained two cases of platform load. In the first case the load was distributed uniformly on the platform. In the second case load of two air pads was decreased and load of two other was increased. Construction of the platform, mathematical models of the controllers and results of investigations have been presented in the paper.

Keywords: *indoor transport, mobile platform, air cushions, pressure control, positioning*

1. Introduction

Presented paper applies to regulation of pressure in air cushions of mobile platform. The platform is in the form of steel frame with four air pads placed under it. The common usage of the platform is a low-range transport of load (from several to tens of meters) inside of factory houses, storage rooms etc. Under the operating conditions, the usual situation is that the load is not distributed uniformly on the platform. Therefore, the differences between values of forces acting on the particular air pads can occur. The necessary requirement for moving the platform is obtaining the proper pressure values in air cushions. For this purpose, the appropriate control system must be applied. In this work models of two regulators have been proposed. Classic PID algorithm has been applied in the first one, while the fuzzy logic has been used in the second one.

2. Object of study

The overall view of investigated platform with the example load and computer data acquisition and control system is presented in Fig. 1.

The platform is a rectangular frame with structural reinforcements. The overall platform dimensions are 1000 x 1900 mm. In order to obtain the proper stiffness, a square section profiles 50 x 50 x 4 mm have been used. Maximum load is 2000 kg. The platform has been placed on four air pads 4LTM-200-1 manufactured by DELU GmbH from Germany. The air pads have the following parameters: operating pressure $p_{op} = 0.2$ MPa, theoretical maximum load capacity $L_{max} = 2500$ kg, maximum required air flow rate 700 dm^3/min. Dimensions of the air pad aluminum panels are: 205 x 205 x 31 mm. The typical load-lifting height is h = 12 mm. View of the individual panel is presented in Fig. 2.

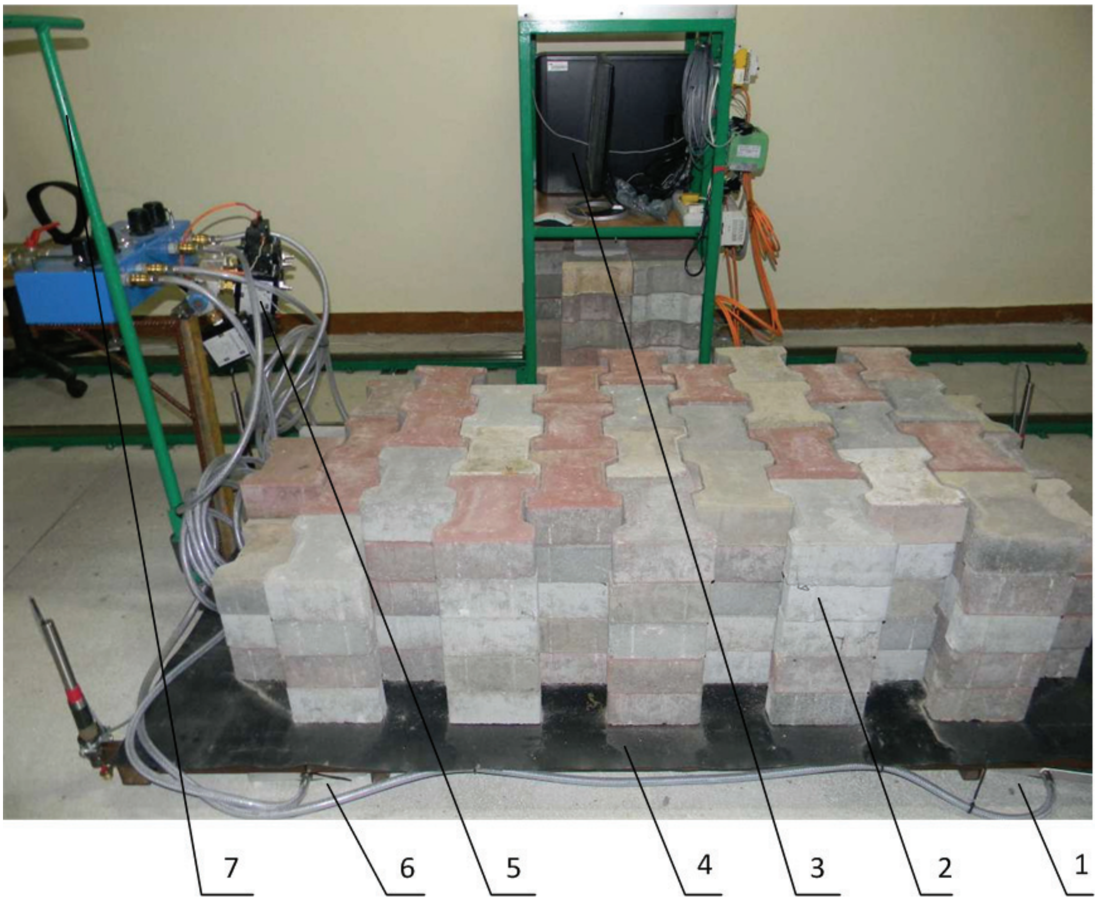

Fig. 1. Object of study: 1, 6 – air pads, 2 – load, 3 – data acquisition and control system, 4 – platform, 5 – proportional valves, 7- handle

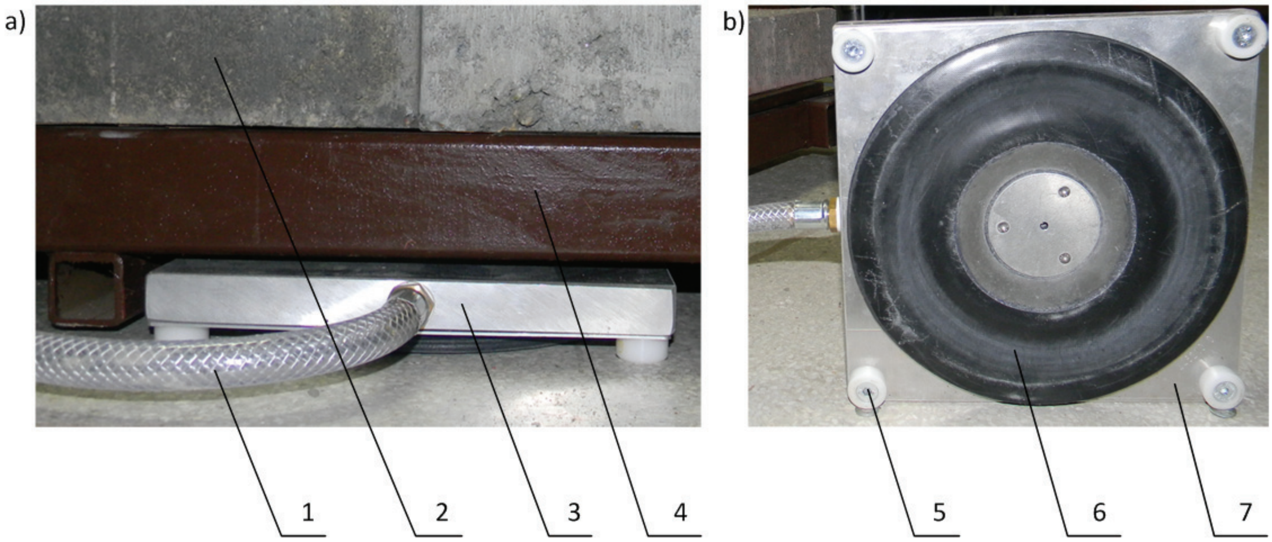

Fig. 2. a) air pad placement: 1 – supply line, 2 – load, 3 – air pad, 4 – platform, b) air pad bottom: 5 – support stand, 6 – air cushion, 7 – aluminum panel

The air pads have been supplied by a pneumatic system. Simplified diagram of the system is shown in Fig. 3.

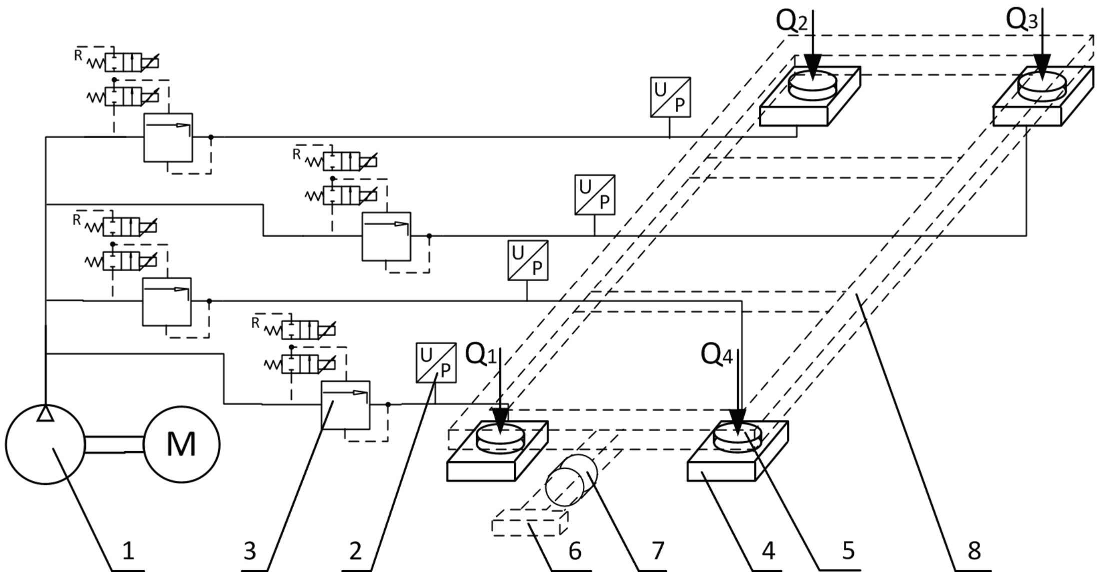

Fig. 3. Simplified scheme of pneumatic system: 1 – supply unit, 2 – pressure transducer, 3 – pneumatic proportional valve, 4 – air cushion, 5 – load force transducer, 6 – handle, 7 – driving force transducer, 8 – platform, Q1 … Q4 - loads

Pneumatic system is supplied by a vane compressor 1, which attains maximum pressure p_{max}=1.2 MPa and delivery Q_{max}=320 dm^3/min. Compressed air supplies four proportional valves 2. A Parker valves, Lucifer EPP4 type have been used. The valves have the following parameters: input pressure p_{in}=1.1 MPa, range of output pressure p_{out}=0.005-0.6 MPa, hysteresis p_h=5.0 kPa, control signal U=0 – 10 V. Pressure transducers 2 are PC-28 type, made by Metronic Systems. They have operational range 0 – 0.6 MPa and output signal 0-10 V. Load forces Q_1 … Q_4 are measured by a ZEPWN CL16U sensors 5 and CL10D transducers. The sensors have operational range 0 – 10 kN. On the basis of obtained force values, required pressures in particular air cushions p_{r1} … p_{r4} are calculated. In the handle 6, additional force sensor 7, CL14U type with CL10D transducer has been installed. It allows to measure operator's driving force. The transducer has range -2-2 kN. In Fig. 4 are shown elements of data acquisition and control system.

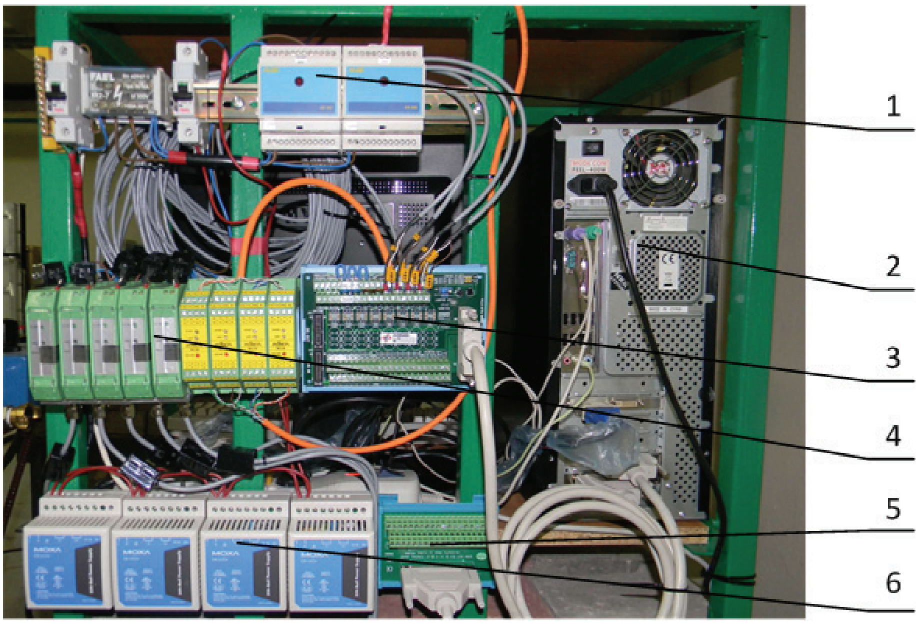

Fig. 4. Data acquisition and control system: 1 –supply units of transducers, 2 – computer station, 3 – DAQ terminal board, 4 – transducers, 5 – control terminal board, 6 – supply units of valves

3. Control strategy

Within a matter of control strategy the following elements have been presented: structure of pressure control system of individual air cushion, model of applied PID regulator and model of applied fuzzy logic controller.

3.1. Elements of air cushion control system

Simplified drawing of the pressure control system of air cushion is presented in Fig. 5.

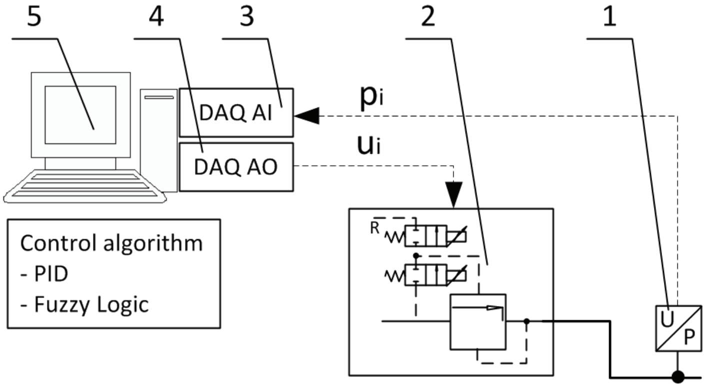

Fig. 5. Control strategy of pressure in individual air pad: 1 – pressure transducer, 2 – proportional valve, 3, 4 – A/D and D/A transducers, 5 – PC computer with the control program

As it arises from Fig. 5, the pressure control system consists of the following components: pressure transducer 1, A/D converter 3, PC computer with a control program 5, D/A converter 4 and proportional relief valve 2. Input signal of control system p_i ($i = 1 \dots 4$) comes from the pressure transducer. The signal is digitalized in A/D converter. For that purpose, a DAQ Advantech PCI-1711 card has been used. The card has 16-channel, 12-bit A/D converter with maximum sampling rate 100 kS/s. Digitalized signal is used for obtaining the value of control error in current step:

$$e_i = p_{ri} - p_i \tag{1}$$

and increment of the control error from previous control step:

$$\Delta e_i = e_i - e_{i-1} \,. \tag{2}$$

Next, on the basis of e_i and Δe_i signals, value of control signal u_i is calculated. The switch in computer program allows using PID algorithm as well as fuzzy logic algorithm. Control signal is converted by D/A unit. In order to control four proportional valves at one time, an Advantech PCI 1720 card with 4-channel, 12-bit D/A converter has been applied.

3.2. Model of fuzzy logic regulator

Mathematical model of the fuzzy logic unit of a FLC type (Fuzzy Logic Controller) has been developed using a three-stage process of the output signal computation. The fuzzification, inference and defuzzification block [3, 6, 7] were created respectively. Modelled FLC is a MIMO (*Many Inputs Many Outputs*) type unit [3, 4], with 8 inputs and 4 outputs. Input signals, defined using the adequate linguistic variables, are as follows: pressure errors e_i and derivatives de_i/dt, where $i = 1 \dots 4$. In the fuzzification block, numerical values of signals are converted to fuzzy sets defined by membership functions. Three fuzzy sets have been defined in range of each input variable: N – Negative, Z – Zero and P – positive. On the basis of the prior research in the area of pressure control and positioning [3, 6] the following shapes of membership functions have been chosen for investigations: linear (triangular and trapezoidal) and Gauss type, defined by the c and σ parameters:

$$\mu_Z(x) = \exp\left(\frac{-(x-c)^2}{2\cdot\sigma^2}\right). \tag{3}$$

Characteristic of pneumatic proportional valve requires using non-symmetric fuzzy sets. Therefore, each membership function contains combination of two Gauss functions, defined by c_1, σ_1 for range $\langle -\infty, c_1 \rangle$ and c_2, σ_2 for range $\langle c_2, +\infty \rangle$ respectively. The following condition must be satisfied: $c_1 \le c_2$. In case when $c_1 < c_2$, the range $(c_1,\ c_2)$ is filled up with value 1.0 [2, 7].

In Fig. 6 are presented diagrams of fuzzy sets defined using linear functions, while in Fig. 7 are shown diagrams of Gauss type fuzzy sets. All input and output signals are normalized. Therefore, in each case computational domain is in range $\langle -1, 1 \rangle$.

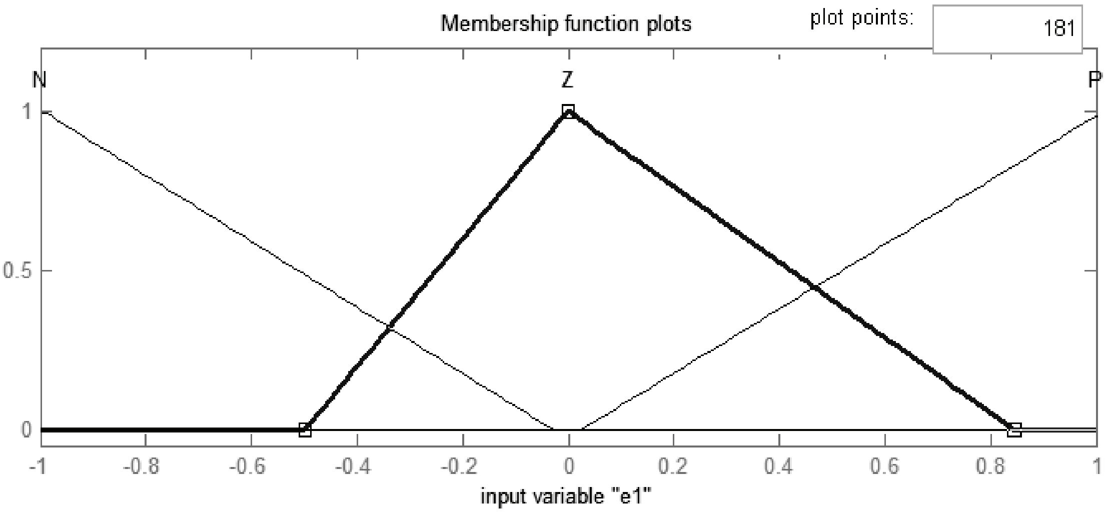

Fig. 6. Definition of fuzzy sets for input signal e1 using linear functions

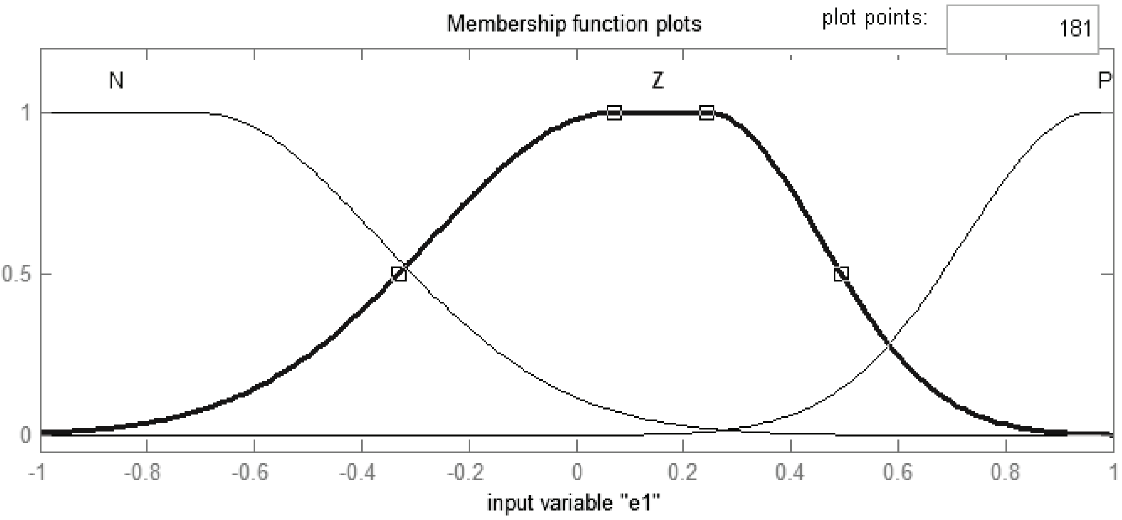

Fig. 7. Definition of fuzzy sets for input signal e1 using Gauss function

Outputs of the FLC are control signals of four pneumatic proportional valves, where the controller generates increments of the signals from previous control step du_i. Domain of each output signal has been divided into 5 fuzzy sets: NB – negative big, NS – negative small, Z – zero, PS – positive small and PB – positive big. There were applied analogous membership functions as for the input signals. Diagrams of fuzzy sets of output signals are shown in Fig. 8 and Fig. 9.

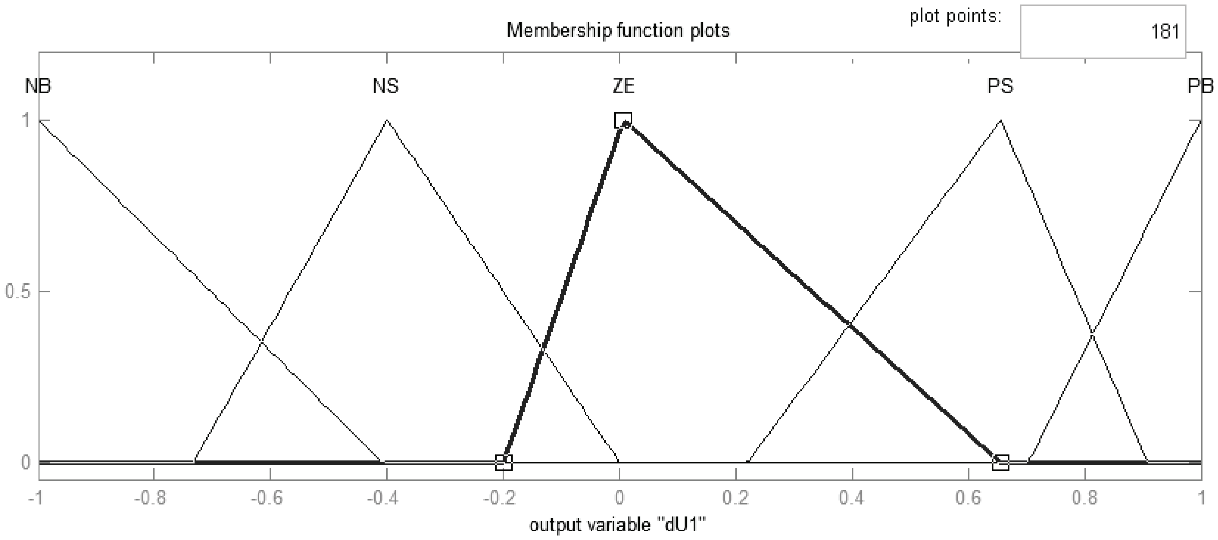

Fig. 8. Definition of fuzzy sets for output signal du1 using linear functions

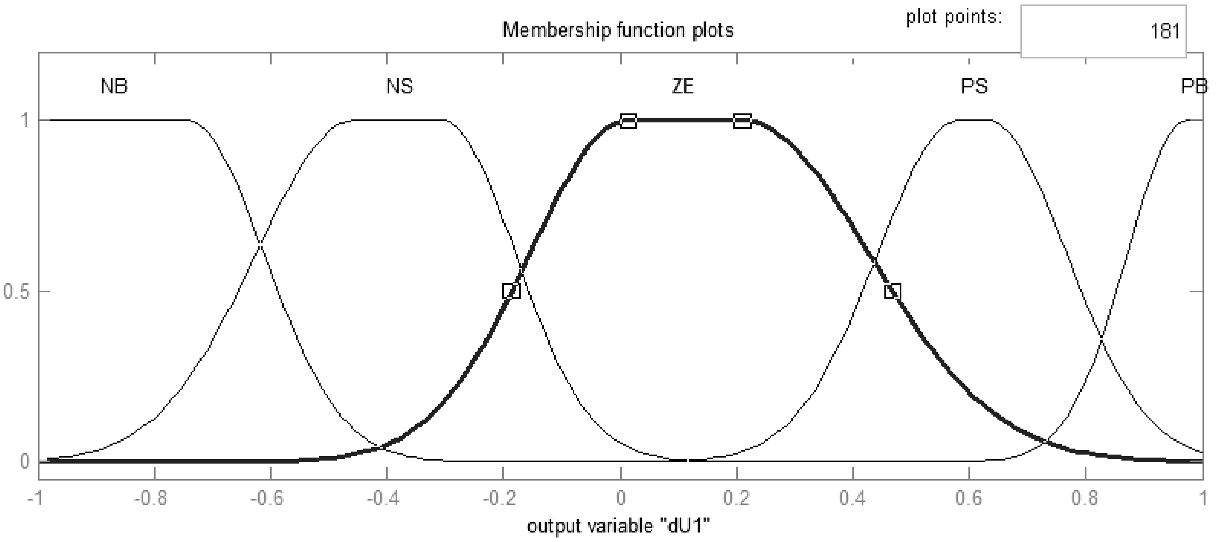

Fig. 9. Definition of fuzzy sets for output signal du1 using Gauss function

The inference process was realized according to Mamdani model [2, 7]. The rule database consisted of 9 rules for each output signal, what gives overall value of 36 rules. There were fuzzified versions of sum (s-norm) and product (t-norm) operators used in rules. Two types of operators were tested: MIN-MAX (4) and PROD-PROBOR (5):

$$\begin{aligned} MIN:&\ \mu_{A\cap B}(x) = MIN(\mu_A(x),\ \mu_B(x)),\\ MAX:&\ \mu_{A\cup B}(x) = MAX(\mu_A(x),\ \mu_B(x)), \end{aligned} \tag{4}$$

$$\begin{aligned} PROD:&\quad \mu_{A\cap B}(x) = \mu_A(x)\cdot\ \mu_B(x),\\ PROBOR:&\ \mu_{A\cup B}(x) = \mu_A(x) + \ \mu_B(x) - \mu_A(x)\cdot\ \mu_B(x). \end{aligned} \tag{5}$$

Defuzzification allows determining numerical value of the FLC output signal on the basis of membership functions values. According to the literature [2, 7], a Center of Gravity (CoG) algorithm has been used.

The control surface of the FLC controller with Gauss-type membership functions and PROD-PROBOR fuzzy operators obtained for valve 1 (control signal du$_1$) in the domain $\Omega = \{e_1 \quad \Delta e_1 \quad du_1\}$ is presented in Fig. 10.

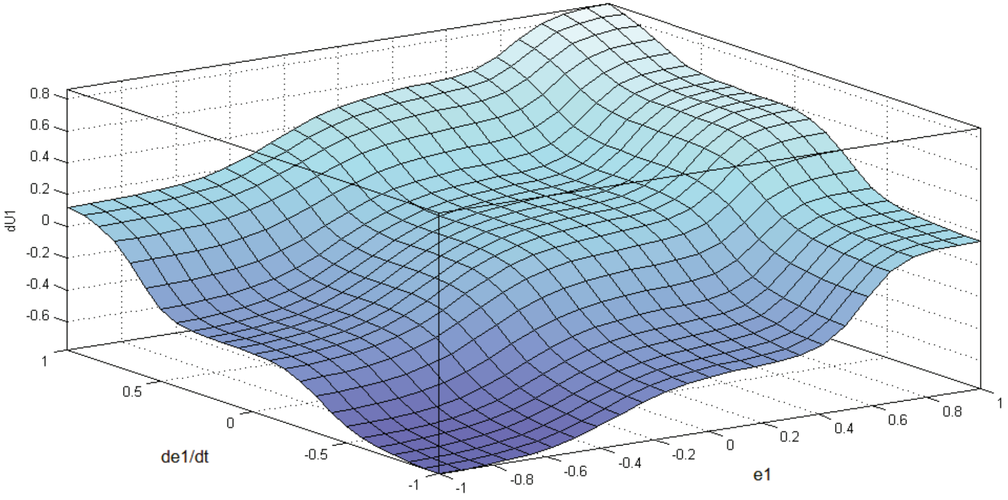

Fig. 10. Control surface of the FLC unit

3.3. Model of the PID regulator

The elementary equation of control signal *u(t)* according to PID algorithm has the following form [1, 4, 5]:

$$u(t) = k_c \cdot \left[e(t) + \frac{\int e(t)dt}{T_i} + T_d \cdot \frac{de(t)}{dt} \right], \tag{6}$$

where:
e(t) - control error,
k_c - gain factor,
T_i, T_d - integral time and derivative time.

In digital control systems values of both input and control signals are calculated in the specified time points (sampling moments). If the control error is determined by equation (1), then the integral can be calculated i.e. using the trapezoid method (7) and the derivative can be approximated by the difference quotient (8):

$$\int e(t)dt = \sum_{i=1}^{n} \left[(e_i + e_{i-1}) \cdot \frac{T}{2} \right], \tag{7}$$

$$\frac{de}{dt} = \frac{e_k - e_{k-1}}{T}, \tag{8}$$

where:
n - number of control steps until the current moment,
e_i, e_{i-1} - control errors in *i* and *i*-1 step, where *i* = 1…k,
T - sampling period,
k - current control step,
e_k, e_{k-1} - control error in current and previous step.

After substituting relationships (7) and (8) into equation (6) the standard form of PID algorithm is obtained [5]:

$$u_k = k_c \cdot \left[e_k + \frac{1}{T_i} \cdot \sum_{i=1}^{n} \left[(e_i + e_{i-1}) \cdot \frac{T}{2} \right] + \frac{T_d}{T} \cdot [e_k - e_{k-1}] \right]. \tag{9}$$

Considering class of hydraulic and pneumatic control systems (including regulation of pressure in air pads), better control effects can be achieved when an increment of control signal is calculated instead of the signal itself. Derivation of the formula for the increment of control signal, also known as the velocity algorithm is presented in [1, 5]. The formula has the following form:

$$\Delta u_k = k_c \cdot \left[e_k - e_{k-1} + \frac{T}{2T_i}\left[e_k + e_{k-1}\right] + \frac{T_d}{T} \cdot \left[e_k - 2 \cdot e_{k-1} + e_{k-2}\right] \right], \tag{10}$$

hence:

$$u_k = u_{k-1} + k_c \cdot \left[e_k - e_{k-1} + \frac{T}{2T_i}\left[e_k + e_{k-1}\right] + \frac{T_d}{T} \cdot \left[e_k - 2 \cdot e_{k-1} + e_{k-2}\right] \right]. \tag{11}$$

The most significant advantage of (11) comparing to (9), indicated in the literature [1, 5], is possibility of calculating control error without numerical integration, which can be a time-consuming and computationally complex process.

4. Results of investigations

Until now, the preliminary investigations with time-constant loads were carried out. In Fig. 11 are presented pressure time courses obtained in case of the same load of all four air pads. Required values of pressure were $p_{ri} = 0.2$ [MPa], while the load of each air pad was $L_i = 250$ [kg] ($i = 1\ldots4$).

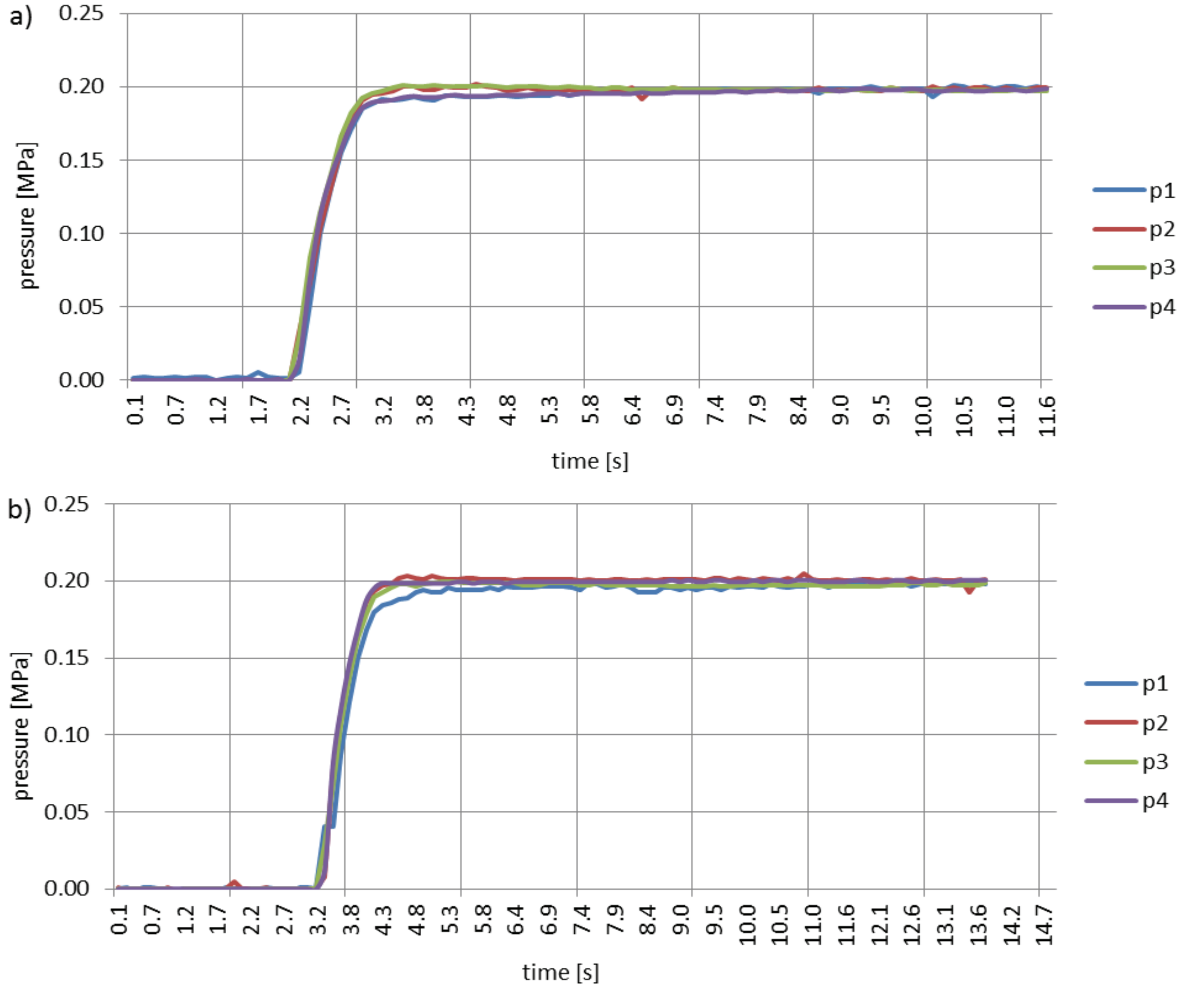

Fig. 11. Pressure time courses with the same load: a) fuzzy logic controller, b) PID controller

The results indicate, that both controllers allowed obtaining required value of the pressure, setting time in both cases was about 1 [s]. However, the FLC course is smoother. The course shown in Fig. 10 was obtained by FLC with the Gauss type membership functions, PROD-PROBOR operators. The other combinations of membership functions types and fuzzy operators gave worse results.

In Fig. 12 are presented pressure courses in case, when the load is distributed non-uniformly. The Q_1 and Q_4 loads were increased to 270 kg each, while Q_2 and Q_3 loads decreased to 230 kg.

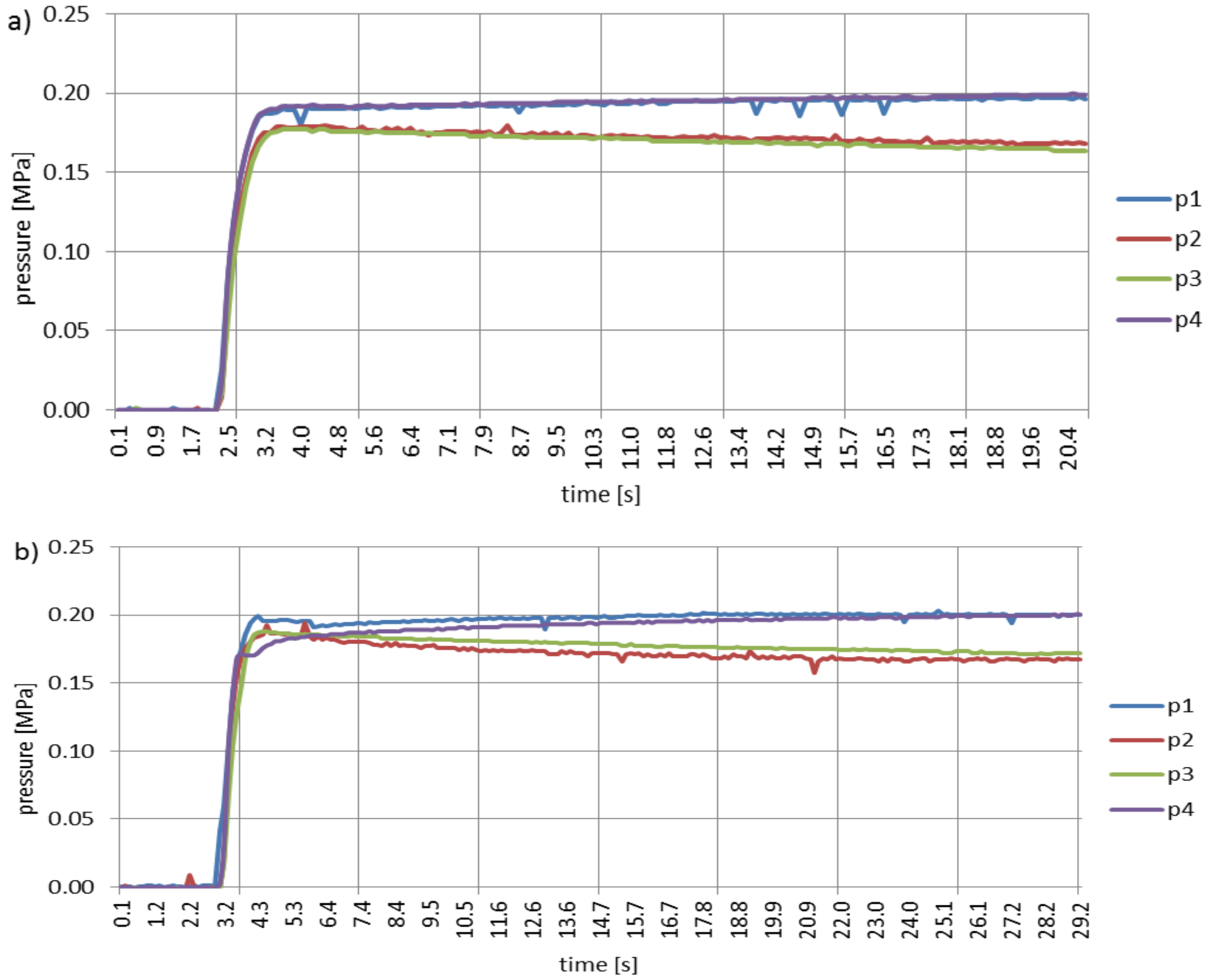

Fig. 12. Pressure time courses with various loads: a) fuzzy logic controller, b) PID controller

In this case the FLC allowed to obtain better results, including smaller differences between pressure values in pairs of air pads 1 - 4 and 2 - 3. When using PID controller, a required value of the pressure was overflown at time t = 4.3 s, what caused opening the exhaust in valve 1 and abrupt pressure drop.

5. Summary

A pressure control system for mobile platform air pads was presented in this paper. Laboratory test platform with four air pads has been built. Both fuzzy logic controller and PID regulator were applied and investigated. It arises from the results, that in case of uniformly distributed, time-constant load, application of both: fuzzy logic and PID algorithm allow obtaining required value of pressure. Using of fuzzy sets allowed making the course smoother. It has been achieved by defining smaller increases of control signal (comparing to PID algorithm), when pressure was close to the required value and larger increases when the control error was large (particularly at the beginning of control process). When the load was distributed non-uniformly, better results have been obtained using the FLC controller. Within a further work, vertical positioning experiments with displacement transducers are planned.

References

[1] Brzózka, J., *Regulatory cyfrowe w automatyce*, Wydawnictwo MIKOM, Warszawa 2002.

[2] Driankov, D., Hellendoorn, H., Reinfrank, M., *An introduction to fuzzy control*, Springer-Verlag, 1996.

[3] Filo, G., *Pressure control in band-saw hydraulic system using the fuzzy logic*, Przegląd Mechaniczny, Nr 5, 2009.

[4] Jędrzykiewicz, Z., *Teoria sterowania układów jednowymiarowych*, Wydawnictwo AGH, Kraków 2000.

[5] Kwaśniewski, J., *Programmable logic controllers*, Wydawnictwo AGH, Kraków 2001.

[6] Lisowski, E., Filo, G., *Pozycjonowanie ładunku podnośnikami hydraulicznymi z regulatorami w logice rozmytej*, Hydraulika i Pneumatyka, Nr 1, s. 30-33, 2010.

[7] Piegat, A., *Modelowanie i sterowanie rozmyte*, Akademicka Oficyna Wydawnicza EXIT Warszawa 2003.