PNEUTRONIC POSITIONING SYSTEM

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This paper contains a new positioning system, along with a mathematical model and control system. The paper discusses the unit's mathematical model, along with a novel control system that includes a microcontroller and a PC interface that allows a user to modify the unit's positioning parameters but also allow the unit to function independently, without the aid of a personal computer.

Keywords: pneutronic, positioning system, microcontroller, virtual instrument

1. Introduction

In today's industrial enviroment, the need for precise positioning of a load is obvious.

Such systems are all subject to the same requirements, without regard to their energy source, such as assuring that a certain precision can be reached, low positioning time, low energy footprint, easily started and maintainted as well as low initial cost.

Thus, when the application requires easily obtained low travel and high speed, low cost and easy maintenance, pneutronic systems are the obvious choice in most cases. These systems are flexibile, have low cost and low emissions and maintaining a position in such systems has a low energy cost, especially in regards to linear positioning.

Working with compressed gas, usually air is however proving to be the biggest drawback for this type of positioning system. Imperfect seals, nonlinear friction, high influence of temperature and enviroment changes, the influence of changes in the pipes that lead the compressed air along with many other factors lead to the well-known non-linear behaviour of such positioning systems.

There is constant and extensive research regarding the improvement of static and transient characteristics of pneutronic positioning systems. Such solutions apply to pneutronic positioning systems that employ either proportional equipment[2][3] or that rely solely on on/off equipment[1][4]. A large portion of

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the published works in the field are oriented towards the control algorithms used to control such systems [5] [6] [7], as well as the electronic control systems.

Using this a a starting point, the authors of this article have designed and implemented a linear pneutronic systems that allows for the testing of control algorithms and the study of disturbances over such systems, in terms of loss of precision and positioning time.

2. The basic schematic of the system

The basic schematic of the system is presented in Fig. 1. The proposed system is composed of a double acting pneumatic cylinder CP, 3/2 controlled using a proportional way valve DPP.

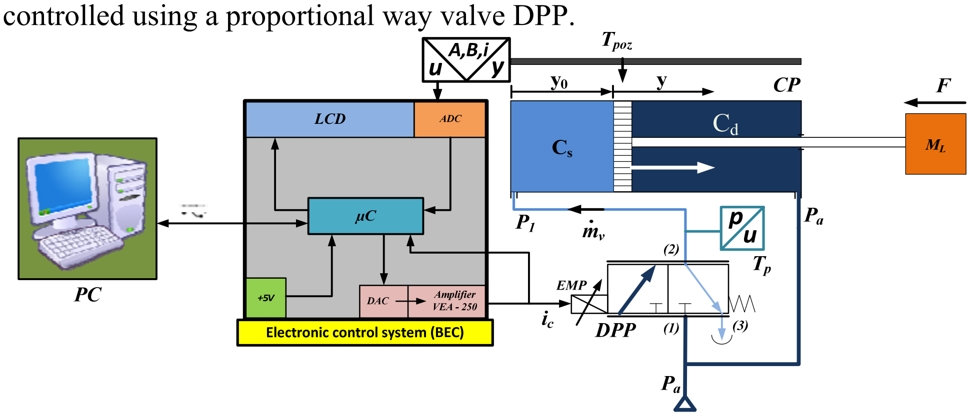

Fig. 1 – The basic schematic of the system

Chamber Cd of the cylinder is permanently connected to the compressed air source Pa. The flow of air through room Cs is controlled through a proportional way valve thus also modifing the air pressure in this chamber. The pressure is monitored by a pressure transducer Tp. The force output of the proportional electromagnet that actuates the slide of the proportional way valve is controlled by current ic controlled by way of a electronic control system (BEC). The movement of the mobile assembly of the cylinder is monitored by using a TIRO position transducer with quadrature output Tpoz. The entire system is supervised by a PC that also gathers data regarding the current state of the system and alows the user to process the data on the spot or at a later time.

In order to control this system, a electronic control system was designed. This is structured around a PIC microcontroller that is responsible for the implementation of the control algorithim, along with data aquisition from the system. The pneutronic system is PC-independent, as the connection between the two is only needed to set the initial values of the control algorithms or change certain parameters during the actual system positioning. Also, through this link the system's parameters are reported at PC level, through a application designed in LabVIEW.

3. Mathematical Model

In this paragraph, using the mathematical model introduced in paper [2] as a strating point, a simulation of the proposed system was created. The simulated mathematical model is considered for the movement of the unit as shown in figure 1. The model can be easily determined for the other direction of movement.

At the basis of the model a series of equations were considered, as follows: The equation of movement for the pneumatic linear actuator:

$$(M_L + M_P)\frac{d^2y}{dt^2} + \beta\frac{dy}{dt} + F_f + F_L = P_1A_s - P_2A_d - P_0A_0 \quad (1)$$

Where M_L is the mass, M_p is the piston-rod assembly mass, y is the movement of the cylinder's rod, F_f is the friction in the cylinder's seals, F_L is the cylinder's force, P_1 and P_2 are the pressures in the cylinder's two chambers, in this case, $P_2 = P_a$ (supply pressure), A_s and A_d are the effective areas for the piston's two chambers C_s and C_d, P_0 is atmosferic pressure and A_0 is the cylinder's rod cross section.

The equation of movement of the way valve slide:

$$M_s\frac{d^2x}{dt^2} + c_s\frac{dx}{dt} + F_f + 2k_sc_s = k_{fc}i_c \quad (2)$$

Where M_s is the slide mass, x is the movement of the slide, F_f is the friction force between the slide and the valve body, *ks* is the spring constant, *kfc* is the proportional electromagnet constant, i_c is the control current and cs is the viscous friction coefficient of air.

c) Equation of flow through the way valve [2]

This equation has been determined for the case where air flow through the valve's flow section A_υ is adiabatic and air is considered to be a perfect gas.

$$\dot{m}_\upsilon = \begin{cases} A_\upsilon C_1 \dfrac{P_1}{\sqrt{T}}, & \text{if} \quad \dfrac{P_a}{P_1} \le 0.528 \\ A_\upsilon C_2 \dfrac{P_1}{\sqrt{T}}\left(\dfrac{P_a}{P_1}\right)^{1/k}\sqrt{1-\left(\dfrac{P_a}{P_1}\right)^{(k-1)/k}}, & \text{if} \quad \dfrac{P_a}{P_1} > 0.528 \end{cases} \quad (3)$$

In equation (3) T is the ambient temperature, C_1 and C_2 are constants that are considered as:

$$C_1 = \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}; \qquad C_2 = \sqrt{\frac{2\cdot k}{R\cdot(k-1)}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k\cdot(k-1)}}}$$

Using adiabatic coefficient $k = 1{,}4\,[-]$ and the ideal gas constant $R = 287{,}04\,[m^2/s^2K]$ the two constants have the values $C_1 = 0{,}04042\ [\sqrt{K}s/m]$ and $C_2 = 0{,}156174\ [\sqrt{K}s/m]$.

d) Valve effective area equation

The way valve controls the effective area of flow Aυ by means of slide 1 that moves under the influence of a proportional electromagnet in bush 2, pressure mounted into the valve's body 3. The bush has a n number of holes of radius *R*.

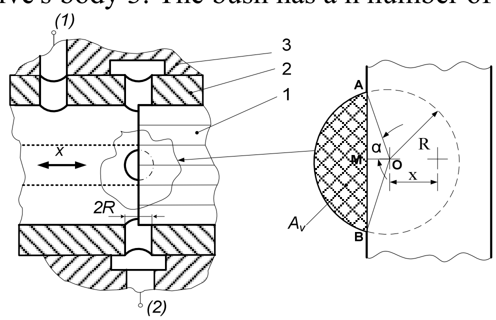

Fig. 2.

As can be seen in Fig 2, the geometric cross section through the equipment is:

$$A = n_h\left(A_{sc} - A_{AOB}\right),$$

where:

$$A_{sc} = R^2 \cdot arctg\,\alpha \quad \text{and} \quad A_{AOB} = (R-x)\left(x\sqrt{2R-x}\right)$$

For triangle AOM:

$$tg(\alpha) = \sqrt{\frac{x(2R-x)}{(R-x)^2}}\text{, that leads to: } \alpha = arctg\frac{\sqrt{x(2R-x)}}{R-x}.$$

Using these equations, the geometric flow section through the valve is:

$$A_v = n_h\left[2R^2\arctan\left(\sqrt{\frac{x}{2R-x}}\right) - (R-x)\sqrt{x(2R-x)}\right] \quad (4)$$

e) Differential equation of pressure in chamber Cs of the cylinder

The evolution of pressure P1 in chamber Cs of the cylinder can be described using the general equation of pressure:

$$\frac{dP_1}{dt} = \frac{kRT}{V_1}\dot{m}_v - \frac{P_1}{V_1}\cdot\frac{dV_1}{dt}$$

where:

$$V_1 = V_{01} + A_1(y_0 + y)$$

where V_{01} is the volume of chamber Cs for y = 0.

Thus we obtain:

$$\frac{dP_1}{dt} = \frac{kRT}{V_{01} + A_1(y_0 + y)}\dot{m} - \frac{nP}{V_{01} + A_1(y_0 + y)} A_1 \frac{dy}{dt} \qquad (5)$$

The mathematical model is composed of equations (1), (2), (3), (4) and (5). This model also contains two nonlinear second order differential equations. By substituting: $\frac{dy}{dt} = v$ and $\frac{dx}{dt} = v_s$

the order of the equations (1) and (2) is reduced and the model will only contain first order differential equations. The model becomes:

$$\begin{cases} \frac{d^2y}{dt^2} = \frac{1}{M_L + M_P}(P_1A_s - P_2A_d - P_0A_0 - \beta \cdot v - F_f + F_L) \\ \frac{dy}{dt} = v \\ \frac{dv}{dt} = \frac{1}{M_s}(k_{fc}i_c - c_sv_s - F_f - 2k_sc_s) \\ \frac{dx}{dt} = v_s \\ \frac{dP_1}{dt} = \frac{kRT}{V_{01} + A_1(y_0 + y)}\dot{m} - \frac{nP}{V_{01} + A_1(y_0 + y)} A_1 \frac{dy}{dt} \end{cases}$$

to which we add algebraic equations (3) and (4).

Where y is the movement of the cylinder's rod, V_{01} is the inactive volume of the end of the stroke, A_1 is the piston's effective area and L is the cylinder's total stroke.

This model can be integrated using specialised subroutines available in different simulation enviroments.

The mathematical model was simulated using Matlab Simulink. Figure 3 shows the previous model under its Simulink form and figure 4 contains the model along with the PI-Fuzzy controller. The system was modelled for Pa = 5 bar and a pneumatic proportional way valve VEP-312 produced by SMC.

Fig. 5 shows the response of the system to a step input. It can be observed that adding a Fuzzy component eliminates overshoot and helps the system reach a stable position much faster. Defuzzification method is max-min and the fuzzy rule set is also containted in figure 5. Positioning error for the simulation is ±0.01mm, with a 3-5 second rise time.

The main performance indicators [6] for simulating this sytem are presented in table 1.

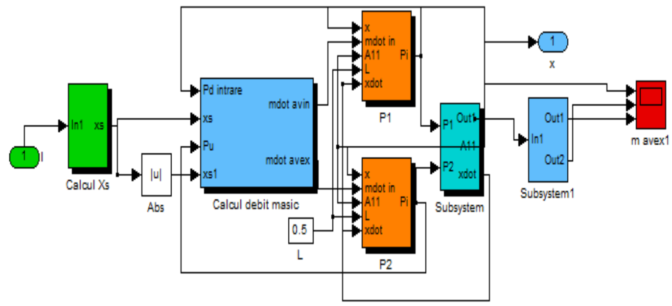

Fig. 3

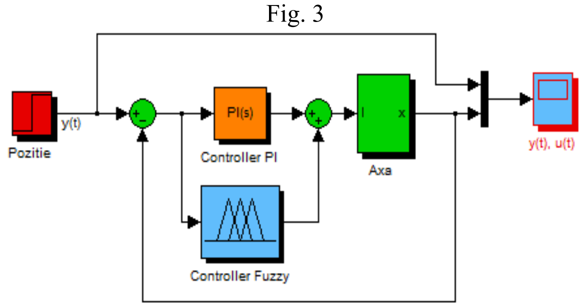

Fig. 4

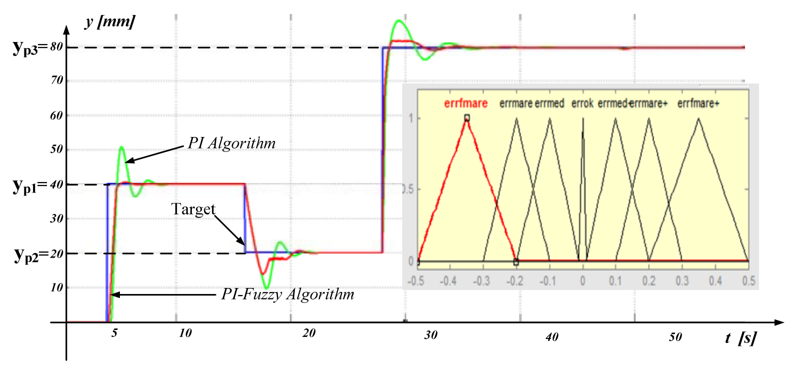

Fig. 5

Table 1

Indicator	PI Controller	PI-Fuzzy Controller
Error [m]	**0,0002**	**0,0002**
Rise time [s]	**0,19**	**0,28**
+ Overshoot(%)	**21,21**	**1,16**
- Overshoot(%)	**0**	**0**
Maximum error [m]	**0,303**	**0,252**
Transient time [s]	**2,89**	**1,38**

4. Electronic control unit and working program

As is the case for most mechatronic systems [11] [12], this positioning unit is controlled by means of a dedicated electronic control system, based on a PIC 16F1937 microcontroller.

The system was conceived in order to control the system, taking into account the fact that the system might need to be modified futher on and thus, more inputs and outputs were created than actually needed. The electronic control system has the below features:

- Working frequency of 32Mhz(4xPLL);
- Three 0 to 5V, 10-bit analog outputs, as dictated by the 10-bit PWM output of the controller
- Three 0 to 5V, 10-bit analog inputs and one 0-10V, 12-bit analog input;
- RS232/USB FTDI interface for PC-PIC communication
- Digital outputs with driver for up to 30V;
- 2x16 alphanumeric LCD display;

The system was programmed using two programming languages in two different programming enviroments, as follows:

- Programming the microcontroller in C++ using Ccs PIC as a compiler. The application allow for position control of the unit at electronic control system level;
- Programming of a graphic application, at PC level, in LabView. This application allow for communication with the microcontroller, control of positioning parameteres and also storing and processing of reported data.

The block diagram of the applications is presented in Fig. 5.

Figure 6 show the front panel of the Labview application. It contains elements needed to select the controller to be used and furthermore, modify controller parameters such as Kp, Ki, Kd, communication configuration to the microcontroller. The interface also allows for position and pressure observation while the system is working. Figure 7 shows the front panel obtained for positioning the unit at 120, 30, 50 and 100 mm.

The front panel allows the user to choose one of 7 control methods of the system, as follows:

- Classic – the control signal for the proportional way valve is raised with a preset increment until target position is reached. If the unit goes past the target position, the control signal is decreased with the same increment;
- P – proportional controller;

- PI – proportional-integrative controller. This controller also contains a output limiting function along with a anti-windup component;
- PID – proportional-integrative-derivativ controller, that also contains output limiter and anti-windup components;
- Fuzzy controller – with triangular rule set predetermined by the code written on the microcontroller;
- PI-Fuzzy – for this controller, a fuzzy rule set is used to autotune the Kp and Ki parameters of the PI controller, based on the system's current error;
- Reference – used to return the system to its refference position, if needed, after the program is started;
- Determine minumim signal – this algorithm is used to determine the minimum value of the output signal that allows for the smallest movement of the unit.

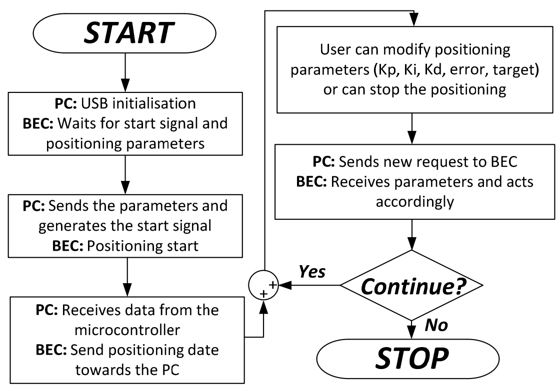

Fig. 6

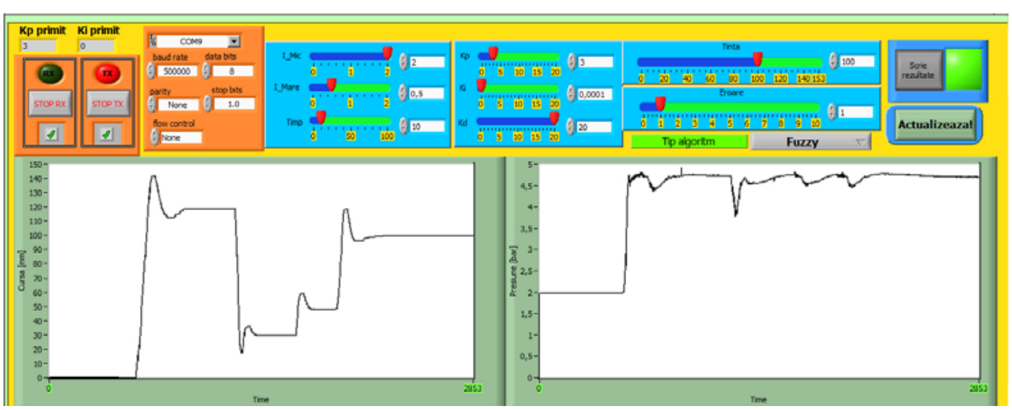

Fig. 7

5. Experimental results

The proposed system was created (fig. 8) and tested. The test stand is comprised of the following elements:

- BEC – rlectronic control system;
- Amp – power amplifier used to control the proportional pneumatic way valve;
- Tp – position tranducer;
- Tp – traductor de presiune
- DPP – pneumatic proportional way valve SMC VEF-312 ;
- TIRO – rotary encoder with quadrature output, used with a COUNTER;
- CP –double acting cylinder, with a 150mm stroke and 40mm bore;
- PC – personal computer with Windows operating system, running Labview programming enviroment;

Fig. 9 shows the system's response to a step input signal. As it can be seen, the system does not achieve a stable position for any of the the Kp and Ki tuning parameters used, which leads to the idea of adding a anti-windup component to limit the influence of the I component on the system.

Following the first set of tests, the derivative component of the PID controller was also introduced into the system. Fig. 10 shows the results obtained for the P, PI and PID with windup. Thus, for the last version of the controller it can be easily seen that the system reaches a stable position.

Table 2 shows the results in comparison, using the main performance indicators specific to PID controllers. The difference between response time, overshoot and undershoot as well as differences between transient times of the controllers used.

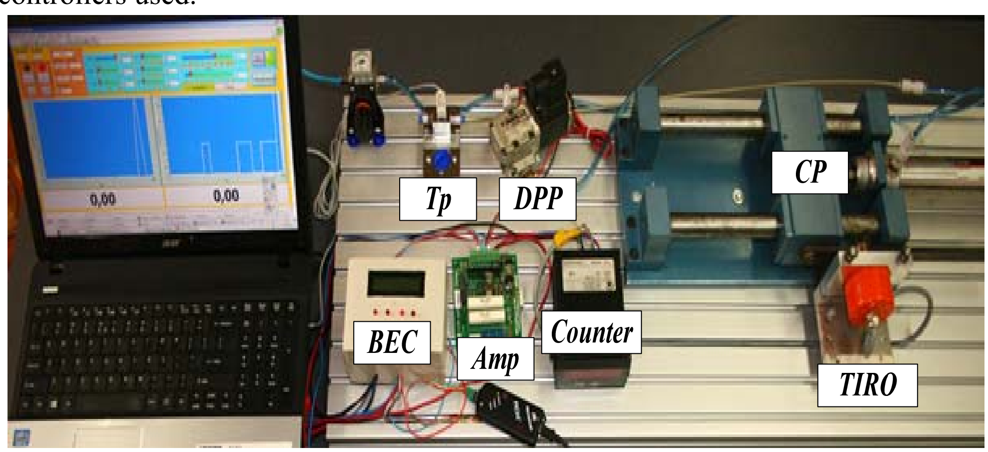

Fig. 8

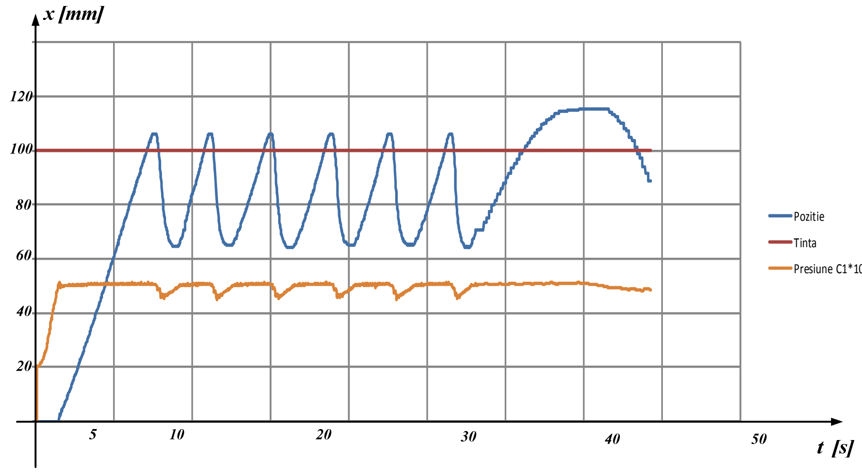

Fig. 9

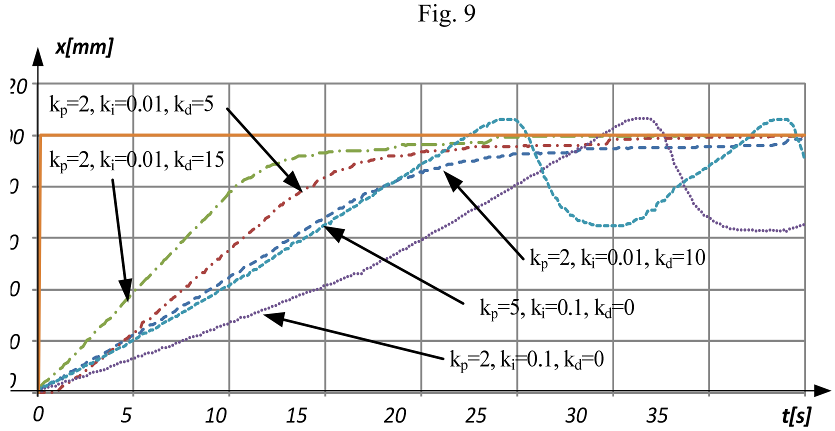

Fig. 10

Table 2

Controller	P	PI	PID anti-windup
Error [mm]	-	-	0.05
Response time [s]	20	18	13
Positive overshoot(%)	10	7	0
Negative overshoot(%)	18	18	0
Maximum error [mm]	10	7	0
Transient time [s]	-	-	18

In order to improve the transient response of the pneutronic positioning system, an adaptive controller was also implemented. This allows the system to work in a discrete manner outside of a tolerance interval, with fixed values for the control signal, relative to the unit's position. Inside this interval, the system uses a

PID, anti-windwup controller, with output limiting. Fig. 11 shows the system's response for positing at 120, 30, 50 and 100 mm. The results show a great deal of improvement in the system's transient time, without any loss in terms of positioning accuracy. However, the system now has a large overshoot (around 25%) of target position.

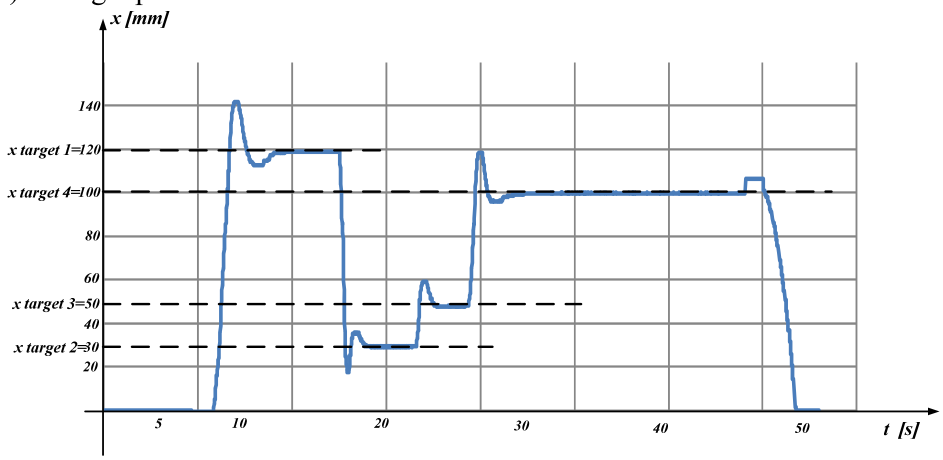

Fig. 11

6. Conclusions

System testing has provided good results for PID control algorithms and the results confirm initial simulation up to this point. The accuracy of the system, with the latest version of the control algorithm is ±0.05mm, with good repeatability. The system reaches this error within 5 seconds of setpoint modification. The authors will continue research on this system by studying the effects of external disturbances on the system in order to improve system response.

In this work the current state of art of pneutronic positioning systems has been studied, particularly in the terms of systems with high positioning accuracy and low positioning time. Based on this study, a pneutronic positioning system has been proposed, simulated and experimentally tested by the authors.

REFERENCES

[1] *Avram M., Constantin V.,* Controlling of a Pneutronic Positioning System, without Proportional Equipment, Romanian Review of Precision Mechanics, Optics and Mecatronics, 2011 (21), No.39, pag.86…89, ISSN 158-5982;

[2] *Edmond Richer, Yildirim Hurmuzlu*, A High Performance Pneumatic Force Actuator System Part 1 - Nonlinear Mathematical Model, ASME Journal of Dynamic Systems Measurement and Control, Vol. 122, No.3, pp. 416-425, 2000.

[3] *Hazem I Ali, Samsul Bahari B Mhd Noor, S.M. Bashi, M.H. Marhaban*, A Review of Pneumatic Actuators (Modeling and Control), Australian Journal of Basic and Applied Sciences, 3(2): 440-454, 2009.

[4] *Željko Šitum, Tihomir Žilić, Mario Essert*, High Speed Solenoid Valves in Pneumatic Servo Applications, Proceedings of the 15th Mediterranean Conference on Control & Automation, July 27-29, Athens-Greece

[5] *Mostafa Marandi, Sassan Azadi* , Design of An Adaptive Neuro-Fuzzy Position Controller For A Pneumatic System - - Proceedings of the International Conference on Man-Machine Systems, 2009;

[6] *Preitl Stefan, Precup Radu-Emil, Preitl Zsuzsa* (2009): Control Structures and Algorithms (in Romanian Structuri şi algoritmi pentru conducerea automată a proceselor). Vol. 1, Editura Orizonturi Universitare Publishers. 272 pp**.**

[7] *J. Falcão Carneiro, F. Gomes de Almeida*, A high-accuracy trajectory following controller for pneumatic devices, Int J Adv Manuf Technol, 2011

[8] *Jakub E. Takosoglu, Ryszard F. Dindorf*, Fuzzy logic positioning system of electro-pneumatic servo-drive, www.intechopen.com

[9] *Tim Wilmshurst*, Designing Embedded Systems with PIC Microcontrollers - Principles and Applications, Elsevier Ltd., 2007

[10] Application Note 655 – D/A Conversion using PWM – Microchip www.microchip.com

[11] *Andrei Drumea, Paul Svasta*, Microcontroller-based electronic module for controlling mechatronic systems, U.P.B. Scientific Bulletin, Series C, Vol. 71, Issue 2, 2009;

[12] *Alexandru Ganziuc, Nicolae Vasiliu, Radu Puhalschi, Szilard Feher*, Using digital electrohydraulic servo valves in fluid control systems, U.P.B. Sci. Bull., Series D, Vol. 75, Issue 4, 2013.