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PWM Control and Identification of Frequency Characteristics of a Pneumatic Actuator using PLC Controller

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Introduction

Pneumatic actuators are widely used in industrial applications due to their advantages over other types of drives such as: easy and simple maintenance, flexibility, low cost, proper power-dimension relation, fast reaction, the possibility to acquire required force and velocity, cleanness, and ability to operate under dangerous conditions.

If servo control is required by means of the pneumatic actuator, it is necessary to use proportional valve in order to control pressure in cylinder chambers. The proportional valve functions as follows: the armature takes some position between entirely open and closed position depending on the electrical signal. Thus the change of flow resistance is achieved. Regardless of the type, the proportional valve is the most expensive component of the pneumatic servo system, which diminishes the above-mentioned advantages of pneumatic drives [1, 2].

Instead of proportional valves and servo valves, on/off electromagnetic valves (2/2 or 3/2-way) are being investigated in order to develop cheap pneumatic servo systems. On/off electromagnetic valves take either entirely open or entirely closed position according to electric command. A pneumatic actuator with on/off electromagnetic valves can be controlled by Pulse Width Modulation (PWM) [3, 4].

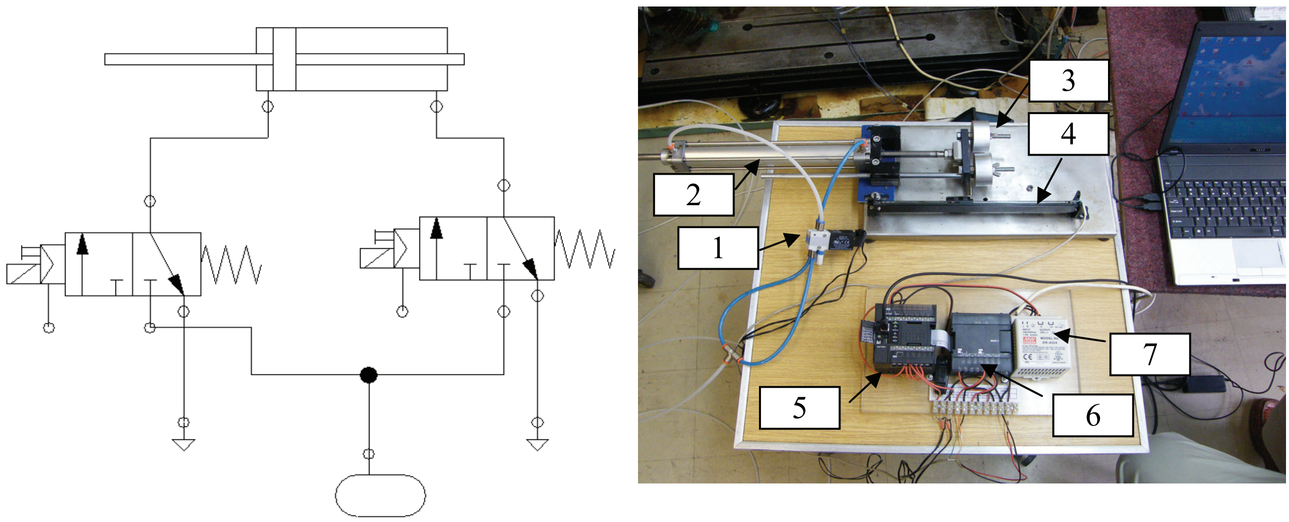
The control done by the pneumatic actuator by means of PWM enables servo control by on/off electromagnetic valves at significantly lower cost than the cost of the control done by proportional valves. If response rate and positioning accuracy are taken into account, the results obtained by PWM control are approximately the same as the results obtained by proportional control.

In the case of proportional valve based systems, the fluid flow is continuously varied. In the case of PWM-controlled systems, the valve is entirely open or entirely closed while the control is done by the time of keeping the valves in final positions. Thus, the valve delivers the discrete quantity of fluid mass whose size depends on control signal. If the frequency of valve opening and closing is much higher than boundary frequency of the system, the system responds to mean value of discrete flow, which is the case of continuous flow, too. By on/off electromagnetic valves controlled by PWM it is possible to develop a multifunctional pneumatic system having acceptable price and performances [5].

To realize PWM control, it is necessary to measure the monitoring error in real time, to estimate the duty cycle of the pulse based on the regulator applied, and to form the command. So far, these tasks have been mostly done by PCs with modules for acquisition or special devices based on microprocessors [5, 6]. Owing to reliability, favourable price, good computer and control abilities and easy maintenance, the programmable logical controllers have a big role in the process control and process automation. In this paper, it is shown how Programmable Logical Controller (PLC) can be used to realize the PWM control of the pneumatic actuator.

System description

In order to test whether PLC could be used for PWM control of the pneumatic actuator, the experimental positional system has been formed as shown in Fig. 1.



a) b)

Fig. 1. Pneumatic scheme and system description: 1– electromagnetic valves, 2 – pneumatic cylinder, 3 – guides and weights, 4 – linear potentiometer, 5 – PLC CP1L, 6 – acquisition module CP1W–MAD11, 7 – DC supply module 24V

The system consists of pneumatic cylinder, electromagnetic valves, a linear potentiometer and a PLC with a module for acquisition. Two electromagnetic 3/2 valves have been used in the experiments, while the experiments done for the cases of one 5/3 valve and four 2/2 valves are stated in the references. In the experiment presented in the paper the normally closed valves have been used, which enables both chambers to be connected to atmospheric pressure; if the constant signal is applied to electromagnets, the chambers are connected to working pressure. In the case of positional error, the pulse series is applied to electromagnets, and their duty cycle is proportional to the error.

The double action cylinder, Ø37x240, with a guide and weights for mass change, has been used. The pneumatic cylinder of unknown characteristics has been used on purpose in order to test whether randomly chosen actuator could be well controlled.

Electromagnetic valve FESTO MHE2 is used to transform the electrical signal into air flow. The characteristics of this valve are small dimensions, compact and easy structure, and very short opening time. The opening time can be either 2 ms for the option when electronics is built-in or 7 ms when there is no electronics [7]. In our case, the electronics is built-in, and it provides shorter response time and decreases the power of electric circuits needed for valve activation.

A programmable controller is a solid state user programmable control system with functions to control logic, sequencing, timing, arithmetic data manipulation and counting capabilities. It can be viewed as an industrial computer that has a central processor unit, memory, input output interface and a programming device. Hardware and software are adjusted to the operation under industrial conditions, so they can be easily programmed and built into existing industrial systems. Historically observed, programmable controllers originate from control systems based on the use of relay diagrams. However, control with the use of PLC enables reliable and efficient functioning and performance that were not characteristic of relay devices earlier. Programming devices provide an operator friendly interface with the machine. Being an out-come of the latest art of electronics technology, PLC provides higher level of performance with computers is possible.

The PLC with two installed PWM outputs Omron CP1L is used in this research. Programmable PWM outputs set the frequency from zero to 6kHz with resolution 0,1 Hz, or from zero to 32 kHz with resolution 1 Hz. The duty cycle of the pulse is also programmable and can be set from zero to 100%, with resolution 0,1% and 1% in the first and second case, respectively. To measure the position, pressure and other quantities within monitoring process, input/output module CP1W-MAD11 is used with two analogue inputs and one analogue output and with resolution of 1/6000 of input range.

Control

If T denotes the period of PWM signal, and T_d denotes the time when the electromagnetic valve is turned on, the following quantity

$$d = \frac{T_d}{T} \qquad (1)$$

is called the duty cycle, and it is expressed in percents.

If u denote the control command for electromagnetic valve, then the signal can be expressed as follows:

$$u = \begin{cases} 24V & za \quad t \le dT, \\ 0 & za \quad t > dT, \end{cases} \qquad (2)$$

where the duty cycle is $d \in [0\%, 100\%]$.

The point of PWM control is that the duty cycle d is calculated based on the error which represents the difference between the given and obtained values, in this case that is the piston position. The value obtained is measured at the potentiometer and transformed by A/D converter, and that value is forwarded to the control unit as a feed back signals. The control unit compares the measured value with the given value and generates the error signal.

There are several methods, which may be used to control the system depending on the control aim and system nature. The problem of regulator structure is solved by defining the control of system output so that the aim of the system is achieved. The common aim is monitoring the reference signal and maintaining the output in case of disorder, which has random or determined character.

The method used in the paper is PID regulator which is theoretically explained and implemented, too. About 97% of all regulators applied in industry is exactly this type of regulators [8]. PID regulator is widely used because it is easy to apply and gives good results if the parameters are properly set.

PID regulator stands for *the proportional, integral* and *differential regulator.* Control signal obtained by PID regulator definition is the sum of three members (3) which represent three methods for processing monitoring error, and they are taken into consideration when the control signal is being formed. When the control signal is being formed the influence of proportional part of the regulator is the biggest in most cases. Amplification quality K_p is set so that the regulator output *u(t)* required level in comparison to the error signal. Integral part of the regulator increases the system order in the closed loop which can significantly change its dynamic characteristics. If the integral influence is increased, the system response becomes faster in closed feedback. The most important property of an integral regulator is its ability to eliminate the static errors. The system described in the paper is integrative in an open loop, which means that there is no control signal, which produces the stationary state at the output. Any command at the system input (except for 0% and when both valves are entirely closed and 100% when both valves are entirely open) results in air flow into one of the cylinder chambers and piston displacement towards one of the final positions. The stationary state is only when both chambers are connected to atmospheric pressure or when the piston has the final position. Differential part of the regulator anticipates the further behavior of error signal based on its speed of change.

The parameters of PID regulator are set directly on the model during an experiment. This setting based on trial and error is not always reliable because it depends on the operator's skill, so the methods for automatic parameter setting have been developed [8].

PID regulator is widely used so most of PLC manufacturers have built this regulator as a part of program environment. By introducing this software realized PID regulator who is integrated into programmable logical controllers it is enabled to control a large number of complex systems, whereas application of PID regulators has become easier and more reliable. The advantage of program-controlled regulators is its simple change of structure and easy parameter setting. Program-controlled PID algorithms conform with theoretical criteria on regulation of continual processes so digital regulator will behave like analogue one by a proper time sampling.

To realize PID regulator at CP1L within the software package CX-PROGRAMMER, the user himself sets the regulator parameters or uses PIDAT by setting the parameters automatically (*PID auto tuning*).

PID algorithm is derived based on the following formula [9]

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)dt - T_d\frac{d}{dt}y(t)\right), \quad (3)$$

The formula (3) is shown that differential action in this option of PID regulator does not apply to the error, but it is applied to the control value. Thus big changes of control value are avoided during sudden changes of the error. Low frequent filtration is applied to the reference signal to avoid large and sudden changes of control value due to disturbance or sudden changes of the reference signal.

For automatic setting of the parameters, the *limit cycle* method is used [9]. The program forcibly changes the control value from its minimum to maximum value, and at the same time it monitors the output. PID constants are calculated based on observed characteristics and after that they are used to estimate the control signal. In the program developed here, the function block PIDAT is called in each scanning cycle (1,2 ms) while the auto tuning of parameters is done only at the beginning of control sequence.

Experimental results

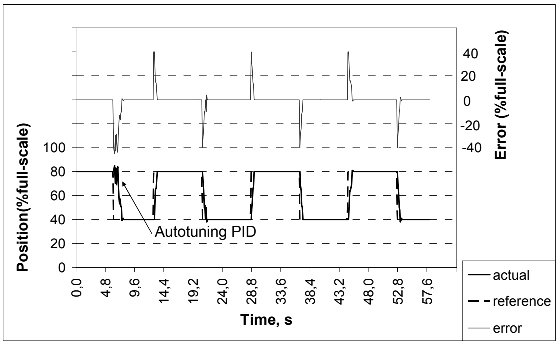
The program for PLC has been developed for described experimental model by using development environment CX PROGRAMMER. Furthermore, the tracking of the reference signal in the form of rectangular pulse series (Fig. 2) and sine reference signal has been tested (Fig. 3). In Fig. 2 is shown the tracking error and calculated duty cycle of PWM signal. The PWM signal frequency of 25 Hz has been chosen due to response time of pneumatic valve and delay in pneumatic lines [4, 5].

For data acquisition and data display PLC is also used as well as the function Time chart monitoring within the program package CX PROGRAMMER. The data are in the file which is later called in from EXCEL for graphical presentation.

Extremely good tracking of the given position has been achieved (Fig. 2) which is the result of well chosen components and proper application of the regulator. In previous experiments in which P regulator was used, the error of 1% to 2% was obtained in the stationary state. The error in the stationary state has been eliminated when PID regulator with automatic parameter setting is applied.

Tracking of sine reference signal of various frequencies has been also tested (Fig. 3). There is almost no amplitude weakening of the frequency of the reference signal of 0,5 Hz, but delay effects are noticeable as well as deformation of the sinusoid due to nonlinear effects. With the increase in frequency of the reference signal, the amplitude weakening occurs, so it is about 4% for the frequency of 1 Hz.

The support is built in the piston rod of the experimental model and the weights can be mounted on it. The following cases have been tested: no additional mass at the piston rod, 2 kg at the piston rod, and 4 kg at the piston rod. The pressure in the pneumatic system in all cases is 5 bars.



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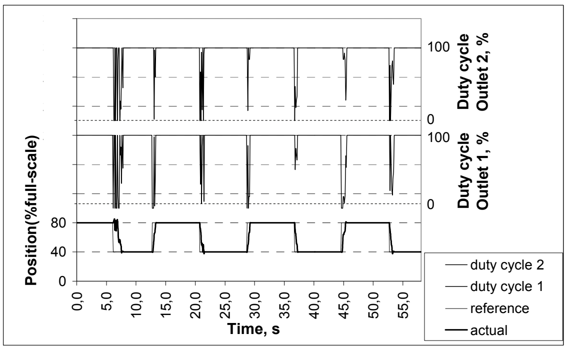
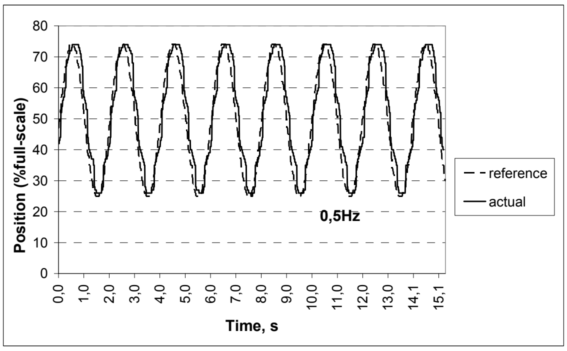


b)

Fig. 2. Tracking the reference pulse signal with the layout of error (a) and duty (b) cycles



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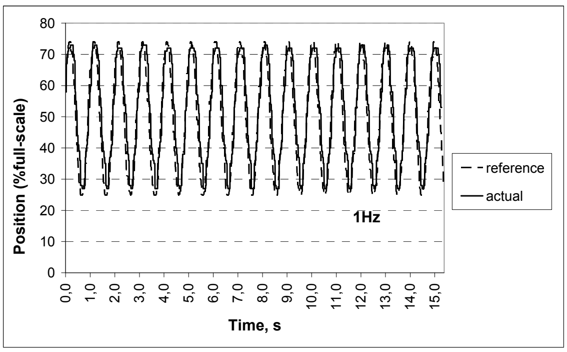


b)

Fig. 3. Tracking the sine reference signal

The tracking remains good if the mass increases when the error in the stationary state is in question, but the transient quality gets worse. The transient becomes more and more oscillatory with the increase of mass. Whether PID algorithm is enough in real application or whether a complex one should be applied, it depends on the requirements of the concrete actuator.

Determination of frequency characteristics

Frequency method is widely used for analyzing and synthesizing engineering systems. It is well known that this method can be applied to studying the systems of different physical nature (electrical, mechanical, hydraulic, etc.), and that it enables dynamic characteristics of these systems to be studied, too. However, in the control of many complex processes a suitable model of the system is not necessarily available. Under these circumstances, more information about the system can be obtained by performing suitable experiments. Experimental data can be used to obtain a parametric model of the system, or can be used directly for the frequency response.

In order to apply this method in actual practice, it is necessary to identify the frequency function of system transfer because of the amplitude and phase frequency characteristics [10, 11].

An algorithm for defining frequency function of system transfer $W(j\omega)$ is based on the following characteristic of its complex transfer function $W(s)$

$$W(s) = \angle \{dy_h(t)/dt\}, \quad (4)$$

where $y_h(t)$ is the system response ($y_h(0_+) = 0$) to the unit step input [12].

If the following is assumed for step response $y_h(t)$

$$\lim_{t \to \infty} y_h = const, \quad (5)$$

then frequency transfer function can be written in the following form based on (4)

$$W(j\omega) = \int_0^\infty e^{-j\omega t} \cdot dy_h(t). \quad (6)$$

If integral (6) is approximated by the sum by final increment $\Delta y_h(t)$ instead of differential $dy_h(t)$ and if the range of integration is limited to the interval of increment, in accordance with (5), the following is obtained

$$W(j\omega) = \sum_{n=1}^{N} \Delta y_h(t_n) \cdot e^{-j\omega t_n}, \quad (7)$$

where N is total of sampling points $y_h(t)$ in which the increment $\Delta y_h(t_n)$ is calculated, where the increment is

$$\delta(t_n) = \Delta y_h(t_n) = y_h(t_n) - y_h(t_{n-1}). \quad (8)$$

Furthermore, series of points of frequency axis ω_1, $\omega_2, \ldots.. \omega_M$ is sampled in order to define the value of frequency transfer function $W(j\omega_1)$, $W(j\omega_1), \ldots.., W(j\omega_M)$.

Matrices are used for presenting complex transfer functions in sampling points in order to do the calculation by digital computer.

Using (7), the matrix equation is written as:

$$\begin{bmatrix} W(j\omega_1) \\ . \\ . \\ . \\ W(j\omega_M) \end{bmatrix} = \begin{bmatrix} e^{-j\omega_1 t_1} & . \; . \; . & e^{-j\omega_1 t_N} \\ . & & \\ . & & \\ . & & \\ e^{-j\omega_M t_1} & . \; . \; . & e^{-j\omega_M t_N} \end{bmatrix} \cdot \begin{bmatrix} \delta(t_1) \\ . \\ . \\ . \\ \delta(t_N) \end{bmatrix}, \quad (9)$$

i.e.

$$\overline{W} = E \cdot D\,. \qquad (10)$$

In order to determine complex vector W having length M (the values of transfer function $\overline{W}$=[(jω_1)… (jω_M)]^T) by means of matrix equation (10), it is necessary to experimentally define the vector D having length N (D= [$\delta(t_1)\ldots\delta(t_N)$]^T) and to calculate complex matrix E whose dimensions are (MxN). It depends on the vector of sampling points $T=[t_1 \ldots t_N]$ and frequency vector $\Omega=[\ \omega_1 \ldots \omega_M]$. Matrix E and multiplication (7) are generated in this study by means of MATLAB programme on PC.

Based on the step response shown in Fig. 4, the vector of increment D is determined in one hundred points. By means of PLC and function *Time chart monitoring* the data are placed into the file. The program developed in MATLAB reads the file containing data D, generates matrix E, vector Ω, and calculates the complex vector W based on the equation (9).

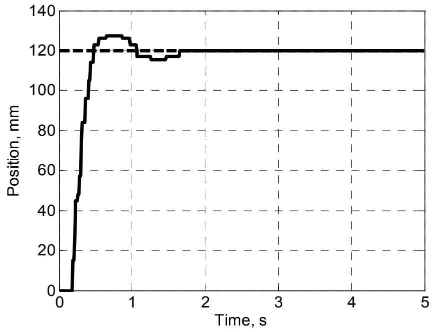


Fig. 4. Step response

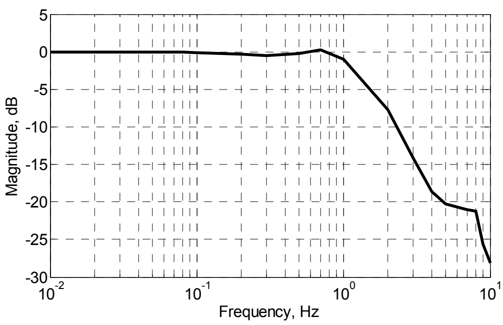
MATLAB programme has useful functions, which make it easy to obtain the frequency response of the linear time-invariant system. Traditional approach to frequency analysis uses Bode diagrams to determine magnitude and phase changes depending on the frequency logarithm.

An amplitude frequency characteristic is defined by means of *abs* MATLAB while the magnitude is defined in decibels based on the well known definition

$$A = 20\log\frac{A_n}{A_0}\,, \qquad (11)$$

where $A_n = abs(W(j\omega))$ and $A_0 = A_n(0)$.

The phase frequency characteristic is defined in the program by the function *angle*. Amplitude and phase frequency characteristics of the described experimental model are shown in Fig. 5.



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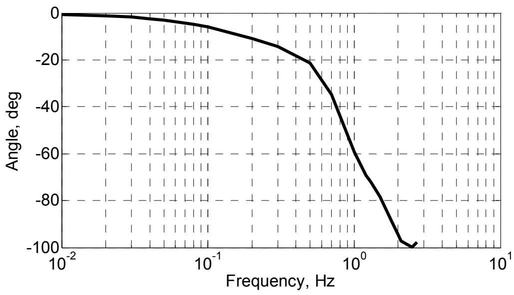

b)

Fig. 5. Frequency response plots

Conclusions

Based on the literature review, it is evident that most of the control strategies available for position control are still not satisfactory. To overcome such deficiencies evident in the literature and to develop accurate pneumatic manipulator, the servo position control has been developed with cheap, standard, on/off valves and commercially available PLC. The control by fast electromagnetic valves has been applied by pulse width modulation Standard PLC has been used for position measurement, error calculation and PWM signal generation. PID regulator, which has been realized at applied PLC, has been used with auto tuning. The paper shows the results of successful experimental implementation on a single degree of freedom pneumatic actuator.

Taking the frequency-domain transfer function as the starting point, it has been emphasized that graphical representations of the frequency response can be derived from data obtained experimentally.

The results obtained show that PWM principle of control gives a good quality of the signal tracking at the considerably lower costs and that PLC with standard program support can be used for its realization.

It has been shown that it is possible to achieve control performances, which are comparable to those achieved by proportional or servo valve but at rather lower cost. Thus, these relatively new and expanding methods of control may be applied as well as pneumatic servo systems. In further research, it will be necessary to test the quality of control at other types of actuators, to apply more complex types of regulators, and to test the described system from the aspect of energy efficiency.

References

1. **Liu S., Bobrow J. E.** An Analysis of a Pneumatic Servo System and Its Application to a Computer–Controlled Robot // ASME Journal of Dynamic Systems, Measurement and Control, 1988. – Vol. 110. – P. 228–235.
2. **Jiing–Yih L., Chia–Hsiang M., Rajendra S.** Accurate Position Control of a Pneumatic Actuator // Journal of Dynamic Systems, Measurement and Control, 1990. – Vol. 112. – P. 734–739.
3. **Barth J., Zhang J., Goldfarb M.** Control Design for Relative Stability in a PWM–Controlled Pneumatic System // ASME Journal of Dynamic Systems, Measurement and Control, 2003. – Vol. 125. – P. 504–508.
4. **Shen X., Zhang J., Barth E. J., Goldfarb M.** Nonlinear Averaging Applied to the Control of Pulse Width Modulated (PWM) Pneumatic Systems // Proceeding of the 2004

American Control Conference. – Boston, 2004. – P. 4444–4448.
5. **Šitum Ž., Žilić T., Essert M.** High Speed Solenoid Valves in Pneumatic Servo Applications // Proceedings of the Mediterranean Conference on Control&Automation. – Athens, Greece, 2007.
6. **Bobrow J. E., Jabbari F**. Adaptive Pneumatic Force Actuation and Position Control // ASME Journal of Dynamic Systems, Measurement and Control, 1991. – Vol. 113. – P. 267–272.
7. **Festo website.** Fast switching valve MHE2 user manual. Online: http://www.festo.com.
8. **Astrom K. J., Hagglund T.** Revisiting the Ziegler–Nichols step response method for PID control // Journal of Process Control, 2004. – Vol. 14. – P. 635–650.
9. **Omron 2005**, CP1H/CP1L CPU Unit programming manual, Cat. No. W451–E1–03.
10. **Eykhoff P.** System identifikation, Parametar and State Estimation. – London: John Wiley, 1974.
11. **Ljung L.** System Identification. – New Jersy: Prentice–Hall, 2007.

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The paper presents a new realization of the positional servo system based on the pneumatic actuator which is controlled by Programmable Logical Controller. The control is done by Pulse Width Modulation and PID regulator is also applied as an integrated function of PLC. The algorithm is implemented at the experimental system which consists of the pneumatic cylinder with double action and two fast electromagnetic valves. The quality of tracking the reference curve in the shape of sine and pulse change has been tested in the experiments. Frequency characteristics of the system have been defined by experimental and calculation method. Ill. 5, bibl. 11 (in English; abstracts in English and Lithuanian).

S. Cajetinac, D. Seslija, S. Aleksandrov, M. Todorovic. Pneumatinės pavaros valdymas ir dažninių charakteristikų identifikavimas naudojant programuojamosios logikos valdiklį // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 7(123). – P. 21–26.

Pateikiama nauja pozicinės valdymo sistemos su pneumatine pavara, valdoma programuojamosios logikos valdiklio (PLV), versija. Valdoma impulso pločio moduliacija bei PID reguliatoriumi, kuris sukurtas kaip integruota PLV funkcija. Algoritmas įdiegtas eksperimentinėje sistemoje, kurią sudaro dvigubos eigos pneumatinis cilindras ir du greitaveikiai elektromagnetiniai vožtuvai. Sistemos dažninės charakteristikos buvo nustatytos eksperimentiniai ir skaičiavimo metodais. Il. 5, bibl. 11 (anglų kalba; santraukos anglų ir lietuvių k.).