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Low air consumption control in pneumatic positioning system

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Działalność naukowa w zakresie identyfikacji, modelowania i sterowania procesów. Obszary badań aplikacyjnych: identyfikacja procesów przemysłowych, synteza algorytmów sterowania dla pneumatycznych układów pozycjonujących, hydraulicznych napędów wyporowych, zespołu napędu hybrydowego o 2 stopniach swobody, oraz pakiety oprogramowania dla identyfikacji układów dynamicznych (IDCAD), i modelowania, symulacji działania i sterowania procesów przemysłowych (PExSim).

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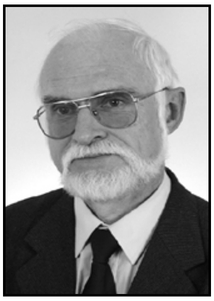

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W roku 2003 uzyskał tytuł magistra inżyniera na kierunku Automatyka i Robotyka. Od roku 2003 jest doktorantem na wydziale Mechatroniki. W 2008 rozpoczął pracę w firmie Schneider. Jego praca naukowa koncentruje się na tematyce związanej z zagadnieniami sterowania ekonomicznymi, pozycjonującymi napędami pneumatycznymi. Opracował 4 publikacje. Przygotowuje zgłoszenie patentowe w zakresie energio-oszczędnego sterowania pozycyjnego siłownikami pneumatycznymi.

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Abstract

The paper presents an idea of an open-loop control of a pneumatic positioning system consisting of a pneumatic cylinder, inexpensive measurement system and four on-off switching valves. A strategy of two or three pulses on-off control trajectory for implementation of a determined piston displacement without an overshoot is presented. Parameters for the control are determined by the application of an artificial neural nets that have to be trained before the application. A control error resulting from open-loop control method can be removed in an adaptive way, proposed in the paper. The strategy is nearly time-optimum one and results in a short control time, quiet valves action and significant reduction of the compressed air consumption in comparison to other pneumatic positioning systems. The idea of this way of control was tested in many simulation experiments and in tests performed in a laboratory. It can be a basis for attractive, low-cost, economic positioning systems.

Keywords: adaptive open-loop control, low cost systems, pneumatic positioning.

Energio-oszczędne sterowanie w pneumatycznych układach pozycjonujących

Streszczenie

W pracy przedstawione została metoda pozycjonowania w układzie złożonym z siłownika pneumatycznego, prostego układu pomiarowego oraz zespołu 4 zaworów przełączających. Zasada sterowania w trybie otwartym układu opiera się na wypracowaniu sekwencji 2-3 pulsów sterujących zaworami, która prowadzi do przemieszczenia tłoka bez przeregulowania. Parametry określające czas trwania pulsów są wyliczane za pomocą sztucznych sieci neuronowych. Powstająca odchyłka pozycjonowania jest usuwana poprzez adaptacyjne dopasowanie sekwencji sterowania. Metoda jest zbliżona do czaso-optymalnego sterowania i prowadzi do minimalne-go zużycia powietrza oraz cichej pracy zaworów. Proponowana metoda została przebadana drogą symulacyjną oraz przeprowadzono pierwsze udane próby na stanowisku badawczym.

Słowa kluczowe: adaptacyjne sterowanie w torze otwartym, pozycjonowanie pneumatyczne. układy ekonomiczne.

1. Introduction

Recent development in electronics and mechanical construction of fluidic cylinders creates the possibility of development of quite new automatic control devices - fine positioning systems composed of a cylinder with a servo-valve, measurement system and controller based on a one-card computer [4, 5, 9]. This construction can cope with traditional electric servomechanism system since it has a better force-to-mass ratio and is cheaper than electric construction [5, 9]. Moreover pneumatic systems are clean, can operate in hazardous environment and are very attractive for new generations of manipulators [9].

Wide implementation of fast calculation chips with a large memory on board enables us to implement advanced digital control algorithms in pneumatic positioning systems [4, 5]. Application of adaptive state space controllers with on-line observers [1, 3], together with very fast proportional valves and short sampling interval of 1 (or even less) ms, has resulted in positioning systems which achieve positioning error below 0.1mm and movement speed more than 1,5 m/s [4, 9]. A structure of such a positioning pneumatic drive is presented in Fig. 1a.

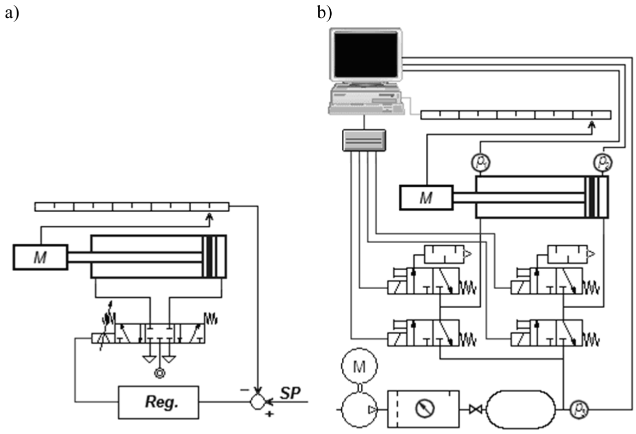

Fig. 1. a) A structure of a modern pneumatic servo-drive with the 5/3 servo-valve, b) Structure of a development system servo-drive with four switch valves
Rys. 1. a) Struktura pneumatycznego serwo-napędu z zaworem proporcjonalnym 5/3, b) Układ badania serwo-napędu z 4 zaworami przełączającymi

One should also mention a group of drives, in which an expensive proportional valve is replaced by two-position switching valves (alternatively working) with PWM-like control technique [10]. This solution however, increases air consumption and due to the noise generated (by PWM modulation) is hard to accept in practical applications.

Among others servo-systems, the positioning pneumatic drive is characterised by a high dynamic, advantageous power-to-weight ratio and overloading capability [9]. But its traditional structure has a number of drawbacks: leakages of the proportional servo-valve and continuous action of the used controller activating the valve (even in the steady state) increase considerably the compressed air consumption [9]. Advanced control algorithms require us to have a precise and expensive measurement system for the estimation of speed and acceleration of the piston for the state space controller [2, 5]. Also the cost of the proportional servo-valve is significant. A specific behaviour of the state space control is presented in Fig.2, where typical transients of the position, speed and control signals [4, 5] are plotted. The state space control algorithm has to prevent an overshoot in the positioning so in the first 200 ms it drives as fast as possible, but in the last phase of the movement (ca. 600 ms!!) it very carefully and slowly approaches to the required final position. This slow phase of the movement makes an average piston velocity to be quite low (four times less than it is possible). Other observation is very important too: the activity of the servo-valve (after first 80 ms) is PWM-like, it yields many steps of subsequent filling and emptying of cylinder volumes with compressed air, and results in unnecessary air consumption and loud noise.

The main aim of the proposed control approach is to reduce air consumption in positioning system. It is implemented in two ways: replacing the expensive, proportional 5/3 valve with remarkable internal leakage by four fast switching valves, Fig. 1b, which have negligible leakage and the application of quasi time-optimal control composed of only several steps: opening, and closing the cylinder volumes what results in small air consumption and short control time.

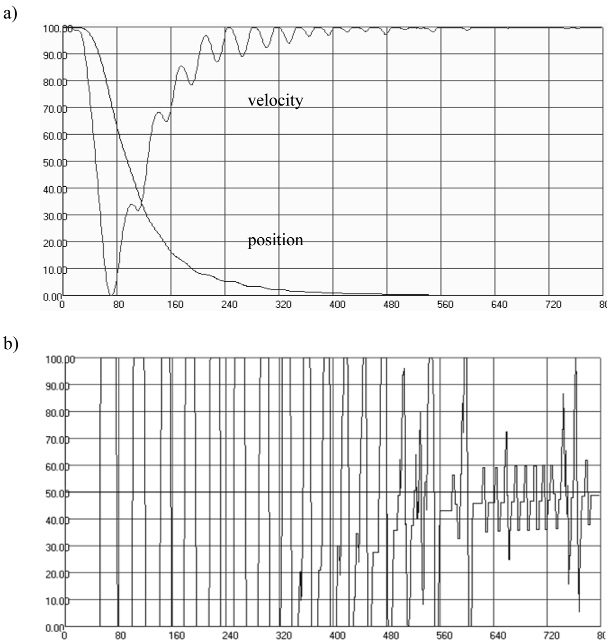

Fig. 2. Transients of: a) piston position and velocity, b) controller output in the pneumatic servo-system with the state-space control

Rys. 2. Przebiegi: a) położenia i prędkości tłoka, b) wyjście z regulatora w układzie pneumatycznego serwo-napędu z algorytmem zmiennych stanu

2. Proposed way of control

The considered drive control is to achieve the fast positioning with a moderate final position accuracy, significantly reduced positioning time and consumption of the compressed air, Fig. 1b. The idea of time-optimal control of a pneumatic drive is based on the usage of four fast switching valves, Fig. 1b, that are controlled directly [2, 6], and final position is reached without overshoot or with the negligible one.

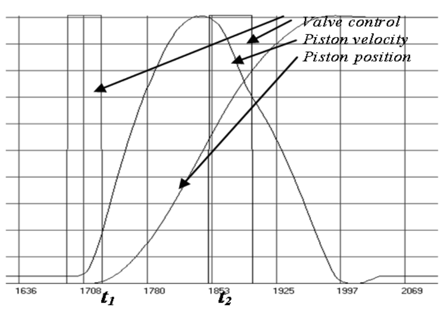

Fig. 3. Simulated position control with quasi time-optimal algorithm

Rys. 3. Modelowane przebiegi pozycjonowania z czaso-optymalnym sterowaniem

A resistive position transducer is used for the supervision of the piston movement and adaptation in the case of observed malfunction. An example of simulated transients of this type of control is presented in Fig. 3.

Considered control strategy is based on the pre-calculation of switching times [2, 6] for each of four valves before the piston movement. In the first phase of control, two switches are active: the first switch is supplying a cylinder volume with higher pressure, while the second is emptying volume that has a lower pressure. A time length of this interval t_1 controls a piston displacement. The second time interval $<t_2, t_3>$ is used for filling of both volumes with compressed air, in order to achieve a high air pressure in both volumes that holds piston hard in the final position. The selection of time instant t_2 is calculated with the use of a special algorithm to avoid an overshoot in the last phase of the movement. The length of time interval t_3-t_2 depends on the required final position and the piston displacement. The transients presented in Fig. 3 result from one control strategy. Many of them are tested [2] with respect to achieved required parameters: controllable piston displacement, lowest piston overshoot and high final pressures in both volumes. Strategies for the determination of the time instants t_1, t_2 and t_3 are quite complex and will be discussed later. Most important is the fact, it is possible to have the control with deterministically defined trajectory, very small or no overshoot, and with in fact the least possible air consumption. The emptied volume has to lost some air, and in fact this air loss is minimal in the proposed control trajectory – after the displacement, both cylinder volumes are filled with high-pressure compressed air, ready for the next piston stroke.

In order to reach the set position with desired level of the displacement error and overshoot, it is crucial to adjust the timing (t_1, t_2, t_3) of the control signals which are responsible for the opening and closing the inlet and outlet valves of the pneumatic actuator volumes. In order to discover proper rules, many experiments have to be conducted – the timing depends on the: initial position, cylinder length, desired piston stroke, supply air pressure, moved mass, valve characteristics and what is very important but hard to determine – friction conditions in the cylinder. In order to reduce the research time, the first part of this investigation has been performed with a fast prototyping approach. A simulation package PExSim (Process Explorer and Simulation) [7] has been used for the simulation of different control strategies [2]. In pneumatic positioning systems, the basic is the precise handling of friction in cylinder, what is very hard to be measured. To perform a realistic simulation, measured transients of the piston velocity have been used for optimal fitting the Stribeck model of friction together with valve flow parameters for the system shown in Fig. 1b.

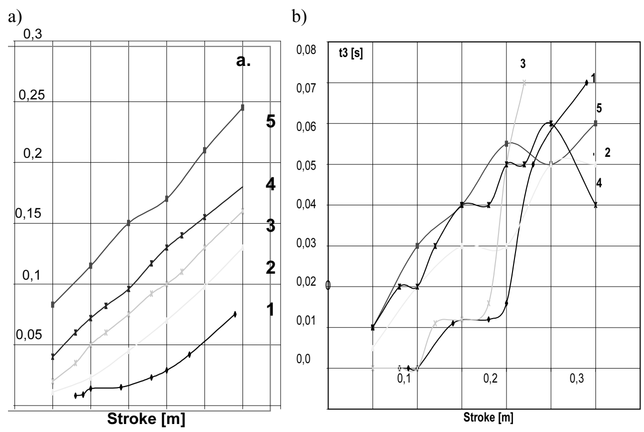

Fig. 4. a) Value of the opening time t_1 and piston stroke, b) Value of time t_3 and the piston stroke for different initial air pressure values

Rys. 4. a) Długość pulsu początkowego t_1 i skok tłoka, b) Czas otwarcia t_3 i skok tłoka dla różnych poziomów ciśnienia zasilania

The optimization is performed with the application of a unique possibility of PExSim – optimization of defined parameters of shell models with respect of generally defined performance index [7]. The simulation research has resulted in a huge basis of control transients (over 500 runs) that have a small or negligible overshoot within the piston displacement. An investigation of these transients has yielded different relations, sometimes very hard to explain. For example, Fig.4a, a relation between the piston stroke Δx and the valve opening time t_1 for the different initial air pressure (marked with integer values near curves) in volumes is expectable and an approximation can be easy, but a corresponding relation of time t_3, Fig. 4b, is hard to explain and to estimate by any reasonable deterministic function. After the testing of different approximation methods for the development of compact rules for the calculation of the times t_1, t_2, t_3 an application of neural networks has been considered, and a set of three multi-layer perceptrons is used – each one to determine the single parameter t_k as a relation between the supply pressure, actual position and set position. A verification of the determined parameters is arranged by the tests of the proposed control using the model of the drive. Almost 90% out of 250 tests are good, i.e., the final position is reached without the overshoot.

In order to cope with the piston displacements where the desired stroke is not reached with a required accuracy (of 1 mm) and/or the overshoot is higher than assumed, an adaptive algorithm is proposed. This approach is based on the assumption that pneumatic positioning system is operating in repeatable cycles what is true in over 99% of applications. Therefore, the introduced open-loop control can be successively corrected, starting from some initial set of parameters t_1, t_2, t_3 and correcting them in each cycle. General idea of this approach is based on the observation, what time parameters t_k have an effect on the displacement length Δx or overshoot η. For example – for length of displacement is responsible time t_1, as shown in Fig. 4.a. An increase of t_1 gives an increase of Δx. Hence, a simple formula for the adaptation of time t_1 can be used

$$\Delta t_1 = \lambda \frac{\Delta x_d}{t_{1n}}(\Delta x_d - \Delta x_r) \qquad \lambda \in < 0.1, 0.7 > \qquad (1)$$

where Δx_d is a required piston stroke Δx_r is a realized piston stroke, t_{1n} is the value of the parameter t_1 calculated by a neural net, and λ is learning coefficient. Similar approach is used for the adaptation of parameters t_2 and t_3 for joint, adaptive correction of the overshoot. Simulated transients show that the adaptation occurs within 4-5 cycles after the initial determination of parameters by the neural nets. The reduction of the displacement error can be decreased to 0.5 mm and overshoot to 1 mm.

Such simple adaptation rules need a relatively small computational power of the processor. The only more time-consuming calculations – neural net formulas for the initial evaluation of parameters t_1, t_2, t_3 are made before the start of on-line control and adaptation. The measurement system that is used only for the position detection (not for the estimation velocity or acceleration) can have a moderate quality and price.

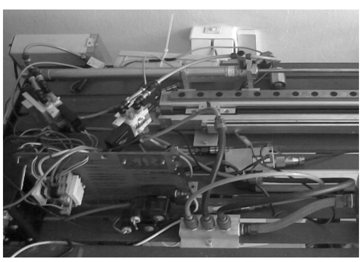

Fig. 5. Stand for tests of the economic control pneumatic control system
Rys. 5. Stanowisko badawcze ekonomicznego układu pozycjonującego

The fast prototyping phase is now completed with the testing of proposed control approach on a test stand, Fig. 5. Of course, some corrections of the invented control are necessary, but first tests are quite optimistic, see Fig. 6. As it is shown a control without the overshoot and a very fast displacement are possible and can be implemented in real conditions. The corresponding control consists of three steps, results in a very low air consumption and is quiet, what is very uncommon in other solutions of the pneumatic positioning systems. The lower the sampling interval, the better is the adaptation correction that can work all the operation time.

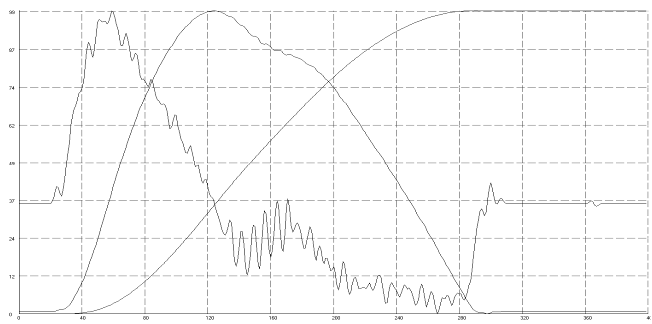

Fig. 6. Transients of the open-loop control: piston stroke, velocity and acceleration
Rys. 6. Przebiegi sterowania optymalnego: skok, prędkość i przyspieszenie tłoka

3. Conclusions

The paper presents a certain approach, and only main problems investigated at research, but it shows the important conclusion: the fast pneumatic positioning system with a very low air consumption and low price can be technically realized. It has cheap components, is able to perform the positioning with the acceptable accuracy and adaptively reduces errors resulted by variable working conditions. The application of such system can be very attractive for all of the manipulation or packaging tasks in which electrical systems are not allowed or are to expensive. Recently some reduction of application number of pneumatic positioning drives due to high cost of compressed air is observed. The proposed approach can reduce at least some these disadvantages and allow the pneumatic systems to keep its competitive position on the market.

The limited accuracy of the approach results from the open-loop control that does not have a feed-back action within the same piston displacement, but for applications working in repetitive cycles, the feed-back can be replaced in part by the adaptive action of algorithm.

4. References

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Artykuł recenzowany