ABCM Symposium Series in Mechatronics - Vol. 1 - pp.399-408

EXPERIMENTAL COMPARISONS OF THE CONTROL SOLUTIONS FOR PNEUMATIC SERVO ACTUATORS

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Abstract. *This paper points to the control problem of the pneumatic servo actuator in positioning, comparing through experimental tests a commercially available industrial controller and classic linear controllers. Although there are many papers covering the control of servo pneumatic drives, was observed the lack of a comparison involving these proposed and tested control strategies with controllers that have recognized use in industry. This paper begins with the presentation of the experimental system where the comparison work was developed. It continues with a short study of mathematical models of pneumatic systems to know the main non-linearities involved. At sequence, P, PI and PID controllers are described and compared with commercially available Festo SPC-100 controller through experimental tests, where are measured the following variables: pneumatic actuator position, position error, pressures in the actuator chambers and the valve control signal. Graphics to each controller are plotted and analyzed. As main paper result, it is possible to emphasize that this is the first study covering one of rare industrial controllers designed to use with servo pneumatic drives. It is seldom used and is practically unknown in Brazil. These experimental results permit that researchers verify the form that these systems are developed in industry and which results are considered as satisfactory. The authors intend to contribute in the study and research of advances in pneumatic servo actuators control to open the doors to new industrial applications for these systems.*

Keywords. *Fluid power, servo pneumatic drives, pneumatic automation, control systems.*

1. Introduction

This paper points to the control problem of the pneumatic servo actuator in positioning, comparing through experimental tests a commercially available industrial controller and classic linear controllers. Although there are many papers covering the control of servo pneumatic drives, was observed the lack of a comparison involving these proposed and tested control strategies with controllers that have recognized use in industry.

According to Scholz and Zimmermann, (1995), the market share of servo pneumatic drives in the automation market still is small, but this drive type offers considerable practical advantages as easy and simple maintenance, relatively low cost, generally safe in operation, self cooling properties, cleanness, good power density (power/dimension rate), relatively temperature insensitive, fast acting with high accelerations and installation flexibility.

The pneumatic actuator is very common in industrial application because it is less expensive and simpler when compared with electro mechanical servo drives with equal power density (Nouri *et al*., 2000). Applications with pneumatic actuators are limited when precision and versatility are needed. Pneumatic actuators have many control difficulties, that are caused by their highly non linear system behavior characterized by the compressibility of air, low inherent damping, dead zone, position dependent stiffness, time-dependent frictional effects in the actuator and non linear control valve behavior with discontinuities, which result in instability, unsatisfactory transient response, large positioning errors and limit cycles.

Otherwise, according to Latino and Sandoval (1996), more than 70 % of industrial positioning systems permit position accuracy greater than 0,1 mm and move mass varying from 0,9 to 11,3 kg. These applications can be developed by pneumatic position servo systems.

This scenery permits to foresee that the study and research in the control of the servo pneumatic actuators will bring a rapid expansion in industrial applications to servo pneumatic, in a similar way of occurred with hydraulic systems after the emergence of proportional hydraulic technology.

This paper begins with the presentation of the experimental system where the comparison work was developed (see Section 2). It continues with a short study of mathematical models of pneumatic systems to know the main non-linearities involved (see Section 3). At sequence, P, PI and PID controllers are described and compared with commercially available Festo SPC-100 controller through experimental tests, where are measured the following variables: pneumatic actuator position, position error, pressures in the actuator chambers and valve control signal. Graphics to each controller are plotted and analyzed (see Sections 4, 5 and 6).

As main paper result, it represents the first study covering one of rare industrial controllers designed to use with servo pneumatic drives. It is seldom used and is practically unknown in Brazil.

2. Description of the servopneumatic position system

The servo pneumatic positioning system (Fig. 1 and 2) is formed by one acquisition and control system mounted in a PC microcomputer and one pneumatic system, that is composed by one rodless pneumatic actuator (2) and one proportional directional pneumatic valve (4). Sensors permit measure air system inlet pressure (1), the actuator position (3) and actuator chamber pressures (P_a and P_b), (5) and (6).

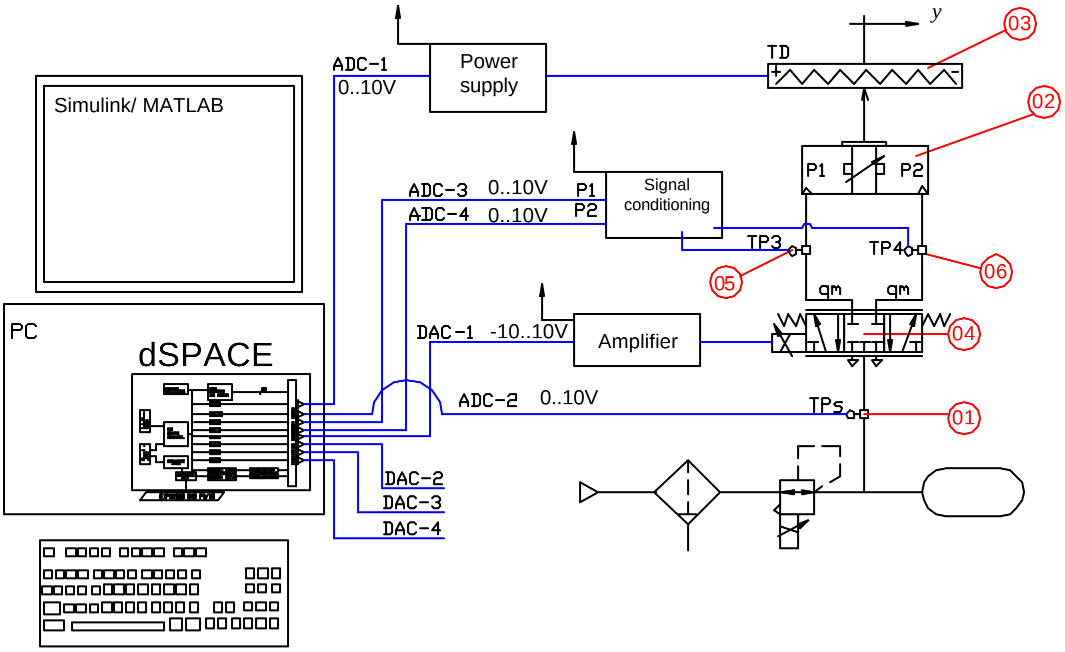

Figure 1. Experimental system configured to servo pneumatic position system tests with P, PI and PID controllers.

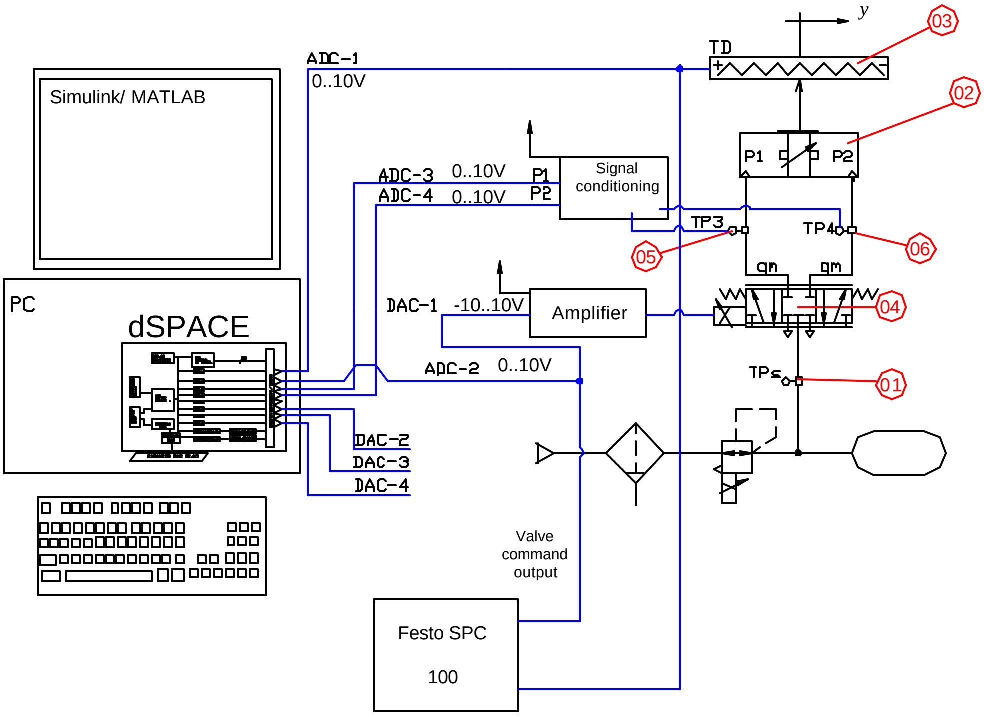

Figure 2. Experimental system configured to servo pneumatic position system tests with Festo SPC-100 controller.

The acquisition and control system used is a dSPACE DS 1102 board (Dspace, 1996). It is an electronic board specially designed to digital control development and data acquisition. It is composed by 4 analog inputs (*ADCs*) and 4 analog outputs (*DACs*). In experiments that involve P, PI and PID controllers, DS 1102 board is used to implement them and to execute data acquisition from sensors (Fig. 1). In experiments where Festo SPC 100 controller is tested, DS 1102 board is used for data acquisition only, according to depicted in Fig. (2). Table (1) presentes the main components of experimental system.

Table 1. Main components from experimental test apparatus.

Component	Maker	Catalog code	Main specifications
Pneumatic rodless actuator	Rexroth	502 602 020 0	Length = 500 mm Diameter = 25 mm
Proportional directional pneumatic valve	Festo	MPYE-5-1/8	5-port, 3-position valve flow rate = 700 l/min.
Pressure sensors	Gefran	TKG E 1 M 1D M	
Position transducer	Festo	MLO-POT-500-TLF	Length = 514 mm
Electronic NC controller	Festo	SPC-100-P-F	
Compressed air reservoir	Pró-Ar	RA 080.500.1	Volume = $2{,}51.10^{-3}$ m^3

3. Mathematic model and system parameters

The study of pneumatic position servo systems is complex when compared with others position servo drives types, because air is very compressible, and has low stiffness, low natural frequency and lubrication difficulties (Santos, 1996). The main equations that model one pneumatic position servo system are the pneumatic valve flow equation, the continuity equation and the load dynamic equation of the system, obtained by the application of the second law of Newton (Vieira, 1998 and Santos, 1996). The simple analysis of these equations permits to foresee that this system presents a strongly non-linear behavior.

3.1. Pneumatic valve flow equation

$$q_m = \alpha \cdot A_o \cdot P_e \cdot \sqrt{\frac{2}{R \cdot T}} \cdot \psi_{max} \cdot \omega(a) \tag{1}$$

where

q_m = mass flow rate;

α is a correction coefficient;

A_o = valve orifice area;

P_e = pressure, upstrean of the valve orifice;

P_s = pressure, downstrean of the valve orifice;

R = ideal gas constant;

T = temperature;

$\psi_{max} = 0{,}484$ is the air critical pressure relation;

and

$\omega(a)$ is a flow rate elliptic function, calculated from:

$$\omega(a) = \sqrt{1 - \frac{(a-b)^2}{(1-b)^2}} \tag{2}$$

when $a > b$, use $a = \left(\frac{P_s}{P_e}\right)$ and $b = \left(\frac{P_s}{P_e}\right)_{\text{críticoreal}}$

or

when $a \le b$, use $\omega(a) = 1$

3.2. The continuity equation

$$q_{me} - q_{ms} = \frac{P}{RT} \cdot A \cdot \dot{y} + \frac{V}{\gamma \cdot R \cdot T} \cdot \frac{dP}{dt} \tag{3}$$

where

q_{me} = input chamber mass flow rate;

q_{ms} = output chamber mass flow rate;

A = ram area;

$\dot{y}$ = actuator velocity;

γ is the ratio of the specific heats of the gas (or adiabatic index);

and

V = chamber volume.

3.3. Load dynamic equation

$$M \cdot \frac{d^2 y}{dt^2} + F_{atr} = A \cdot (P_a - P_b) \tag{4}$$

where

y = actuator displacement;

F_{atr} = actuator friction force;

and

M = load mass.

According to Santos (1996) and Vieira (1998), the most complex non-linearity in pneumatic position servo systems is the actuator friction force. Its presence makes the position control more difficult because it can cause position steady state and position trajectory tracking errors. In addition, friction force can also cause limit cycles around the desired position (hunting) and stick-slip movements.

4. Controllers used in experimental tests

The experimental tests were conducted through individual tests with a Proportional controller (P), Proportional Integral controller (PI), Proportional Integral Derivative controller (PID) and the commercially available Festo controller model SPC-100. This section presents a short description of these controllers. The experimental procedures are described in Section 5.

4.1. Proportional controller (P)

The Proportional controller (P) produces an control signal that is linearly proportional to the error in the measured output, with transfer function D(s) depicted by Eq. (5). The value of the K_P gain must be small in order to keep the system stable. It is also characterized by low robustness, because its gain must be small and a little disturbance or parameter variation can cause instability.

$$D(s) = K_p \tag{5}$$

4.2. Proportional Integral controller (PI)

The Proportional Integral controller (PI) adds a signal fraction proportional to error integral. The transfer function D(s) of a PI controller is depicted by Eq. (6). The system answer becomes more oscillating and its answer can approaches the instability, but the integral part reduces the steady state error.

$$D(s) = K_p + K_I / s \tag{6}$$

4.3. Proportional Integral Derivative controller (PID)

The PID controller has also a derivative part that increases the system damping. Equation (7) depicts its transfer function D(s). The integral presence also can cause stable limit cycles. These gains must continue small to the system to be stable, but its answer is slow.

$$D(s) = K_p + K_d s + K_I / s \tag{7}$$

4.4. Commercially available Festo SPC-100 controller

The commercially available controller used in this work is the SPC-100 Festo controller, that has been designed specially for servo pneumatic drives at industrial applications. It has two closed-loop functions:

- Position control function of a pneumatic actuator;
- Generation of reference variables (reference positions) for a pneumatic actuator.

Beyond this function to position control of a pneumatic actuator, this industrial controller permits the binary signal processing, analog to a PLC (Programmable Logic Controller). This capability allows to apply this controller in hybrid systems control. Figure (3) depicts the application of Festo SPC-100 controller in a pneumatic positioning control system.

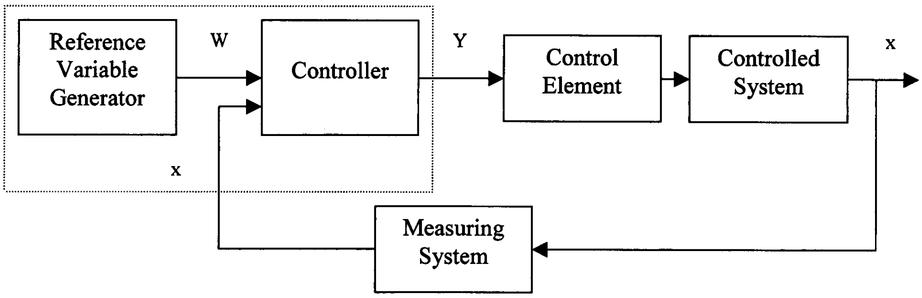

Figure 3. Servo pneumatic position system block diagram with Festo SPC-100 controller (Gerhartz and Scholz, 1994).

The controller hardware is composed by one analog to digital converter (AD converter) at input interface, one digital processor that executes the control program and one digital to analog converter (DA converter) at output interface.

SPC-100 controller works based in a triple loop control structure, with position, speed and acceleration feedback, according to presented through a block diagram by Scholz and Zimmermann (1995). Perondi (2002) also presents one study of the state of the art of controllers with this control structure, applied to pneumatic actuator control. Associated with this state feedback there is an adaptive control, whose control law is not available by maker (Festo, 1993) and by ready literature (Scholz and Zimmermann, 1995 and Gerhartz and Scholz, 1994). The adaptive control permits the automatic adaptation of the control parameters defined by the user in the initial program, to optimize the positioning performance. The measuring system (Figure 3) uses only position as feedback signal, actuator chambers pressures are not used in the control.

According to Scholz and Zimmermann (1995), the programming of trajectory to SPC-100 controller is made through NC (Numerical Control) language commands. One program may be inserted into this controller through display and keyboard that are attached with SPC-100 controller. Other form to program it is through serial interface with a PC (Personal Computer) and specific software. During programming work, user must to provide a list containing the main parameters of the controlled system, that: diameter and length of the pneumatic actuator, air supply pressure, moving mass, maximum allowed actuator speed and acceleration, among others parameters. Also is necessary to insert the control parameters, that: proportional gain, damping, adaptive gain, speed gain, acceleration gain and maximum error allowed in positioning.

5. Experimental tests

The experimental tests have occurred with pneumatic actuator following the positioning sequence defined by Fig. (4). The pneumatic actuator is positioned through steps among the positions $y_0 = 0$ mm (central position of the rodless pneumatic cylinder), $y_1 = 100$ mm and $y_2 = -100$ mm.

These experiments were carried out with air supply pressure of 6,0 bar. The DS 1102 board was configured with a sample rate of 1 ms and acquisition rate of 10 ms. The pneumatic actuator moves a total mass of 1,0 kg.

5.1 Experimental tests with P, PI and PID controllers

In P, PI and PID controllers experimental tests (with experimental system according to Fig. 1), the functions of control, trajectory generation and data acquisition were fulfilled by DS 1102 board. The measured variables were:

- Pneumatic actuator position (y);
- Pressures in the actuator chambers (p_a and p_b);
- Air supply pressure;
- Control signal produced by DS 1102 board (u).

The position error (e) was calculated by subtracting actuator position (y) from position reference (y_d in Fig. 4).

The proportional controller was tested with gains K_P that varying from 1,0 to 100,0. Obtained results have varied from systems with very slow answers and big errors (for small gains) until systems with big oscillations (for great gains). Figure (5) depicts the obtained results with $K_P = 100,0$.

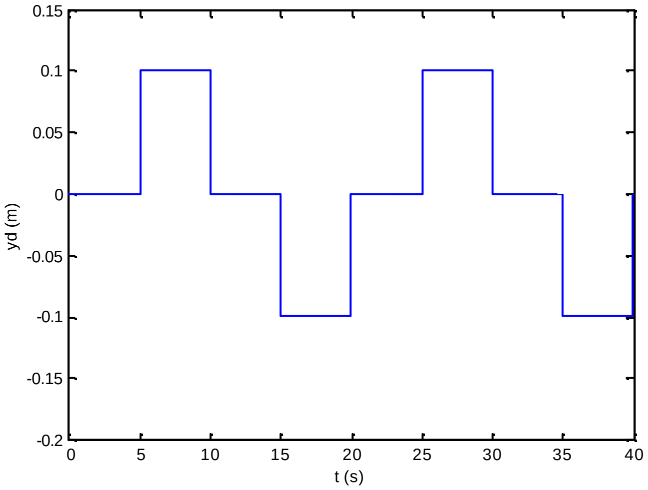

Figure 4. Position reference (y_d) for pneumatic actuator in the experimental tests.

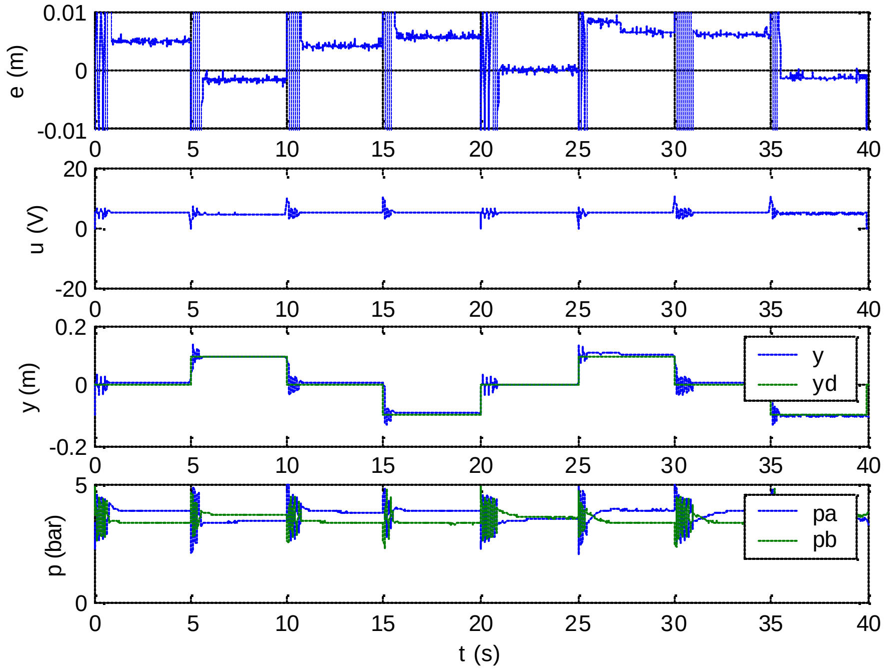

Figure 5. Experimental results with P controller (K_P = 100,0).

The proportional integral controller was tested with K_P gains that varying from 30,0 to 50,0 and K_I gains varying from 1,0 to 30,0. Figure (6) depicts the obtained results with K_P = 30,0 and K_I = 1,0.

Among the tests carried out with PID controller, were select the results obtained with gains K_P = 50,0, K_I = 30,0 and K_D = 2,0. They are depicted in Fig. (7).

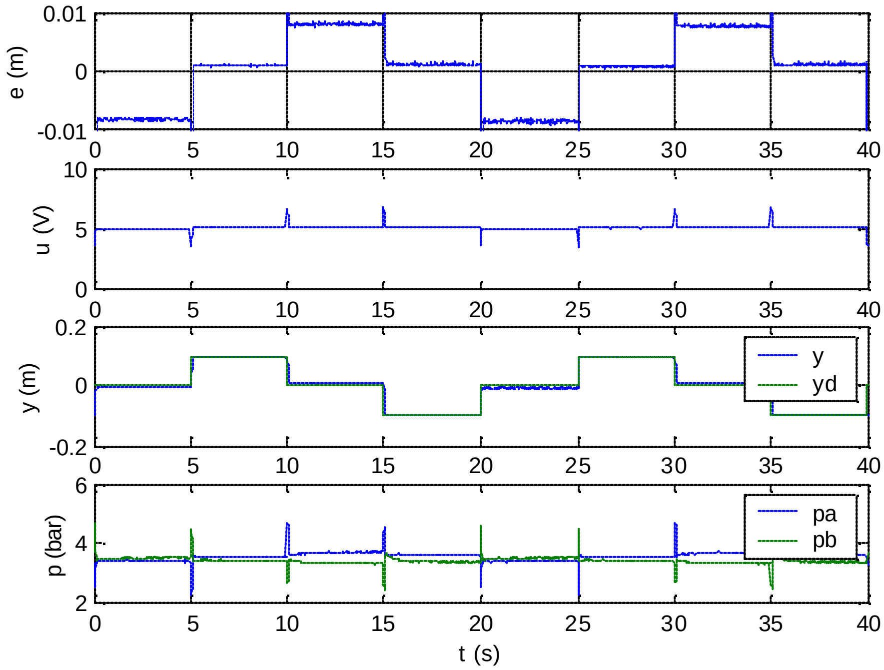

Figure 6. Experimental results with PI controller (K_P = 30,0 and K_I = 1,0).

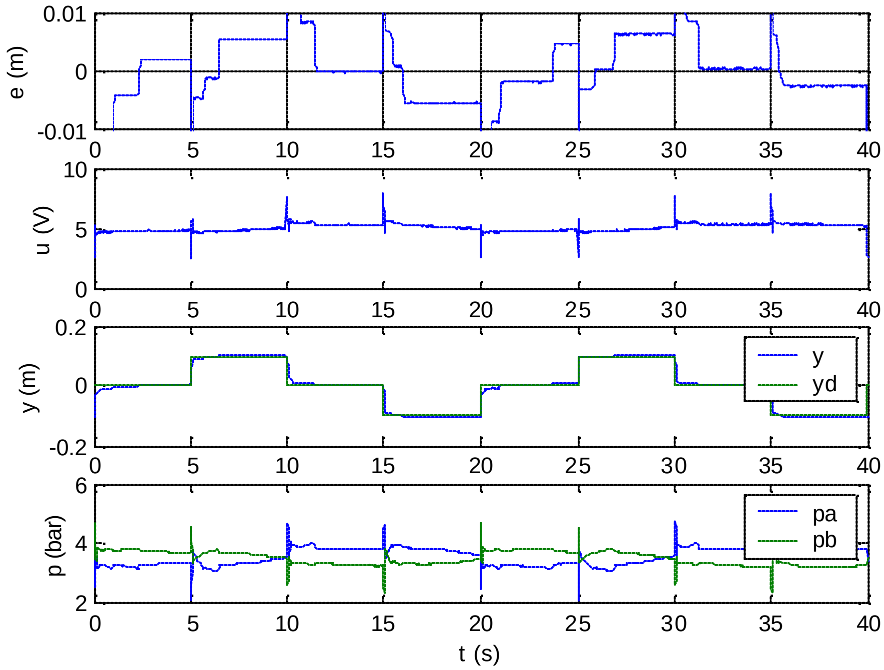

Figure 7. Experimental results with PID controller (K_P = 50,0, K_I = 30,0 and K_D = 2,0).

5.2 Experimental tests with Festo SPC-100 controller

During Festo SPC-100 controller tests, with the experimental apparatus was configured according to Fig. (2), the functions of control and trajectory generation was fulfilled by tested controller and data acquisition was carried out by DS 1102 board. The measured variables were:

- Pneumatic actuator position (y);
- Pressures in the actuator chambers (p_a and p_b);
- Control signal produced by SPC-100 controller.

The NC program developed to fulfil the Fig. (4) trajectory during experimental tests is depicted in Tab. (2).

After programming SPC-100 controller and inserting system and control parameters, the tests were carried out varying the next parameters: proportional gain (P_{gain}), damping (Damp), adaptive gain (A_{gain}) and maximum error allowed in positioning (Toler), that are the main control parameters to configure this controller. Table (3) depicts the possible range for these parameters.

Figure (8) depicts the obtained results with P_{gain} = 2,5, Damp = 1,0, A_{gain} = 1,0 and Toler = 1,0. Figure (9) presents the results obtained with P_{gain} = 2,5, Damp = 2,0, A_{gain} = 1,0 and Toler = 1,0.

Table 2. NC Program of trajectory to SPC-100 controller tests.

NC0	NOP
NC1	G00 A y0
NC2	G04 5s
NC3	G00 A y1
NC4	G04 5s
NC5	G00 A y0
NC6	G04 5s
NC7	G00 A y2
NC8	G04 5s
NC9	G00 A y0
NC10	M30

Table 3. Range of main control parameters for SPC-100 controller.

Control parameter	Possible range
P_{gain}	0,001 to 25000
Damp	0,5 to 3,0
A_{gain}	0,1 to 10,0
Toler	0,02 to 10,0

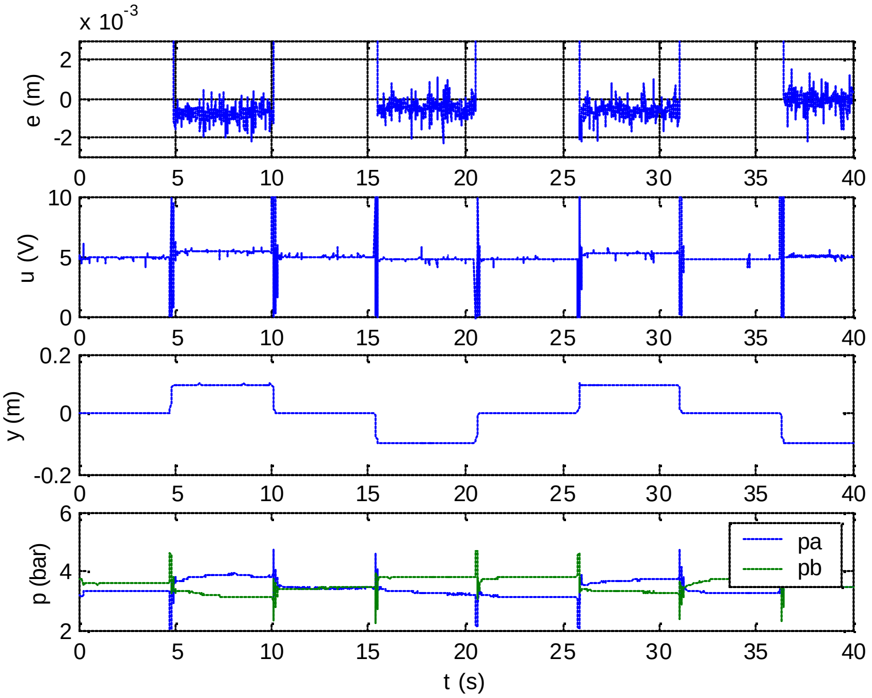

Figure 8. Experimental results with SPC-100 controller and P_{gain} = 2,5, Damp = 1,0, A_{gain} = 1,0 and Toler = 1,0.

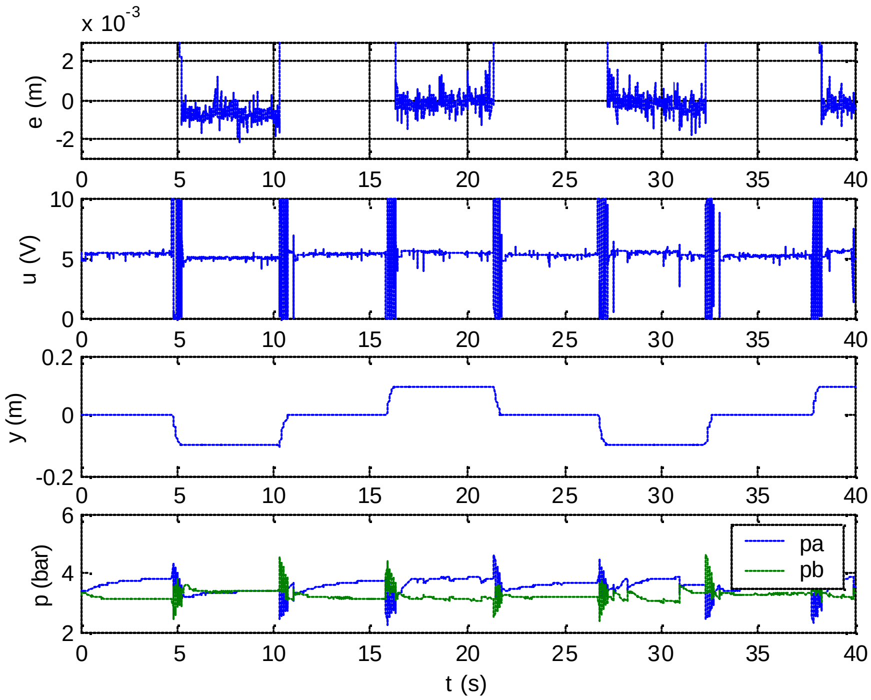

Figure 9. Experimental results with SPC-100 controller and P_{gain} = 2,5, Damp = 2,0, A_{gain} = 1,0 and Toler = 1,0.

6. Analysis of the experimental tests

The application of a P controller in a pneumatic position system demands big K_P gains for reducing the position error, but the control signal is oscillating and there is overshoot in the actuator position.

To minimize the position error without increasing too many K_P gains, was necessary to use an integral part in the controller (PI controller). If the integral gain is too large, occur big overshoots becoming impossible some applications. Also occur hunting problems, that are oscillations caused by limit cycles around desired position.

To solve this overshoot problem, is used a derivative part in the control (PID controller), but the damping increase turns the system more slowly. According to Perondi (2002), the performance of P, PI and PID controllers are limited by open loop poles localization, parameters with possible vague values and because the intrinsically non linearity of pneumatic systems.

SPC-100 experimental results permit to conclude that the gains initially defined by user are modified internally by this controller according to a unknown control law, that is not presented by its maker (according to Scholz and Zimmermann, 1995).

The actuation of adaptive control in the automatic parameter adaptation may be seen by qualitative form only. The SPC-100 controller does not permit to see the modified parameters. This encourages future and deeper studies.

It is known that there is a state feedback (position, speed and acceleration) in SPC-100 controller associated with one adaptation strategy. Because this system is strongly non linear (see Section 3), it is possible to perceive that, for certain initial gains sets, the system performance and control signal are degraded, with the possibility of the system becomes unstable. The system has same performance for different initial gain sets that are near the optimum. The authors have faced a strong difficulty to determine best gain values because the control law that is used in this controller is not known.

The SPC-100 controller is optimized to obtain positioning performance (it is always in search of to reach positioning error that was defined in the initial configuration by user), without considering possible valve damage. This is verified in Fig. (8) and (9) transients and in the others experimental results of this controller (that are not depicted here because the paper limit length), where the control signal (u) is oscillating and reaches saturation. Figure (9) permits to observe that the increase in damping parameter causes more oscillations in control signal, although the rise time is greater and the system presents smaller oscillations.

7. Conclusions and future work

The positioning tests of servo pneumatic drive to compare P, PI and PID controllers with commercially available Festo SPC-100 controller here related permit conclude that the PID controller is limited to precision control. It can be used with success in some applications. For instance, in applications that do not need high positioning precision (error < 10 mm). It is a cheap solution and with easy implementation.

At P controller is associated a poor performance, because it presents great oscillations with reduced error (to big K_P gains) or slow answer with great errors (to small K_P gains). The PI controller reduces the position error, but it damages the system damping that can impede applications that do not permit overshoot.

The tests carried out with commercially controller permit to conclude that the optimum gain set selection is difficult because the user does not know the control law used in this controller and the user needs to define a large number of control parameters. It is difficult to identify the influence of each one of these parameters at control. Although is used an adaptive control, the user can not see the final value of the automatically modified parameters by controller. It is only possible to verify the parameter adaptation by qualitative form.

Compared with classic controllers (P, PI and PID), SPC-100 controller is a solution with relative high cost, but with good positioning performance. Its use sacrifices the pneumatic valve life; according to the analysis of the control signal (u) depicted in Fig. (8) and (9). The programming of trajectory to SPC-100 controller can be made by manual form, where the control parameters and NC sentences are inserted directly by keyboard in controller. It is a hard work because there are an excessive parameter number, user error possibility and the sophisticated programming menu tree. There is a programming interface for PC microcomputer, but its use demands to buy the necessary software, that also represents high initial cost.

The installation of SPC-100 controller to carry out these experimental tests has undergone the following difficulties that probably would be faced in an industrial application:

- The technical assistance by maker is difficult because SPC-100 controller is a product with still restricted use and with little sales in Brazil.
- It is very difficult to obtain literature and handbooks that cover the use and installation of this controller.
- It is hard to determinate the control parameter values because de control law used in SPC-100 controller is unknown and it is difficult to understand the manner that each control parameter changes the positioning performance.

With main result of this paper, it is possible to emphasize that this is the first study covering one of rare industrial controllers designed to use with servo pneumatic drives. Its use still is infrequent and it is practically unknown in Brazil. These experimental results permit that researchers verify the form that these systems are developed in industry and which results are considered as satisfactory. The authors intend to contribute in the study and research of advances in pneumatic servo actuators control to open the doors to new industrial applications for these systems.

How future works after this paper, the authors intend to carry out a study with more depth on the effects in positioning performance caused by changes on control parameters of Festo SPC-100 controller. Also they plan to compare this industrial controller with cascade controller presented by Perondi (2002) and to study forms to friction compensation in pneumatic servo actuators.

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