MATEC Web of Conferences **121**, 08001 (2017) DOI: 10.1051/matecconf/201712108001
MSE 2017

Linear pneumatic actuator

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Abstract. The paper presents a linear pneumatic actuator with short working stroke. It consists of a pneumatic motor (a simple stroke cylinder or a membrane chamber), two 2/2 pneumatic distributors "all or nothing" electrically commanded for controlling the intake/outtake flow to/from the active chamber of the motor, a position transducer and a microcontroller. There is also presented the theoretical analysis (mathematical modelling and numerical simulation) accomplished.

1 Introduction

The actual stage and the future development of pneumatics make it a high technology domain. The successes guaranteed by the results of some fundamental and especially applicative "fascinating" researches [1], in the direction of diminishing the negative effects produced by the physical properties of the working fluid: low viscosity and high compressibility. These are the main difficulties in building high performance pneumatic systems.

The informatisation of the pneumatics systems is an important qualitative step ahead for the domain [2]. The concept of pneutronics was developed by the synergetic joining of three domains: pneumatics-electronics-informatics. So, pneutronic actuating systems were born.

The configuration of such a system may vary from simple actuating circuits to complex structures, controlled with programmable automatons or computers. The basic elements of such a system are the proportional pneumatic servo-systems [3 - 5]. In the structure of the system are also included sensors and transducers, electronic circuits for signal processing, A/D and D/A converters, controllers or microprocessors.

Unfortunately these systems are very expensive and they are rarely used. This is the reason why sustained efforts are made in order to reduce the costs [6, 7].

In this paper a pneumatic linear actuator is proposed. It is in fact a pneutronic positioning system that does not use proportional devices.

2 The structure of the intelligent pneumatic actuator

Figure 1 shows the original principle scheme of the actuator to be developed. It consists of the following elements:

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 DOI: 10.1051/matecconf/201712108001

BPA – the pneumatic supply block;
MPL – the short stroke pneumatic motor;
BEC – the electronic command block;
Tr – the position transducer.

The pneumatic supply block *BPA* delivers into the active chamber of the motor a pressure proportional with an electric command signal: $P_c = f(x_c)$.
For the short stroke pneumatic motor one can choose between special short stroke motor, a chamber with a membrane or a corrugated tube.

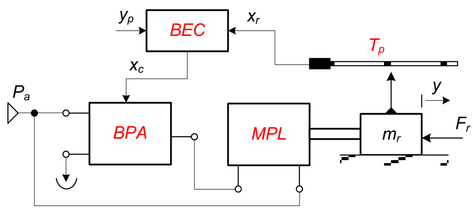

Fig. 1. The original principle scheme of the actuator.

The functional scheme of the actuator is shown in figure 2.

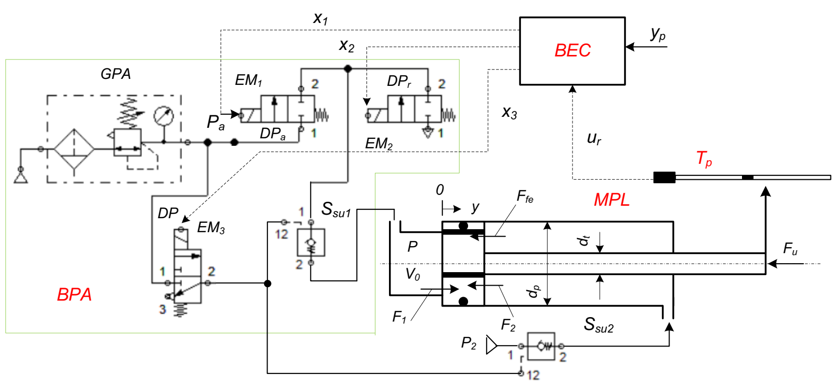

Fig. 2. The functional scheme of the actuator.

The pneumatic supply block consists of the following devices:

- the 2/2 pneumatic control valves DP_a and DP_e, with preferential position, electrically controlled;
- two one-way valves, relievable, S_{su1} and S_{su2}, pneumatically controlled;
- the 3/3 pneumatic control valve DC, with preferential position, electrically controlled;
- the air supply group.

The control valves DP_a and DP_e connect the active chamber of the rod less pneumatic linear motor MPL to the pneumatic supply or to the atmosphere; the chamber has the volume V.

The rod chamber of the motor is permanently connected to the pressure supply. When the control valve DP_a is commanded the pressure P increases; when the pressure force F_1 becomes greater than the force $F_2 + F_{fe}$ (the pressure force and the elastic friction force respectively), the mobile assembly of the motorstartsmoving. The position transducer Tp gives information on the position of the mobile assembly to the electronic command block BEC; at this level, the actual position is in real time compared with the programmed position; according to the result of this comparison, digital command signals are or are not generated for the control valves DP_a and DP_e.

The logic of these signals is the following:

- if $y < y_p - \varepsilon$ then $x_3 = 1, x_1 = 1$ and $x_2 = 0$;
- if $y_p - \varepsilon \le y \le y_p + \varepsilon$ then $x_3 = 0$, $x_1 = 0$ and $x_2 = 0$;
- if $y > y_p + \varepsilon$ then $x_3 = 1$, $x_1 = 0$ and $x_2 = 1$,

where: *"1"* corresponds to the case when the electromagnet of the control valve (*DP*, DP_a or DP_e) is commanded, and *"0"*when the electromagnetic not commanded.

3 The theoretical analysis of the intelligent pneumatic actuator

The static and dynamic performances of a system can be determined theoretically or experimentally. In this stage, without a physical model of the actuator, only a theoretical analysis can be performed.

Taking into consideration the functional scheme and imposing the maximum stroke, the useful force and the supply pressure, the devices composing the system can be pre-dimensioned and then they can be chosen from the producers catalogues.

The next step is the elaboration of the mathematical model and then the simulation of the system functioning. So, the first information on the dynamic behavior of the system is obtained.

Mathematical modeling and numerical simulation are laborious; require knowledge from many domains besides pneumatics (numerical analysis, automated systems theory, computer programming, informatics, optimizing methods etc.).

A pneumatic system is characterized by a large number of variables and interactions that are difficult to quantify, so a rational and systematic approach strategy for modeling and simulation is required.

The mathematical model of a pneumatic system is highly non-linear [8], [9], [10], and the numerical simulation is used to determine the capability of the system to perform a given task, in terms of dynamic behavior.

The equations of the mathematical model are the following:

a. The mobile assembly moving equation is given by:

$$m_r \cdot \frac{d^2y}{dt^2} = F_1 - F_2 - F_{fe} - F_0 - F_u \tag{1}$$

where:

$$F_1 = P \cdot S_1$$

$$F_2 = P_2 \cdot S_2$$

$$F_0 = P_0 \cdot S_t$$

$$F_{fe} = \mu \cdot \pi \cdot d_p \cdot b_p \cdot (P_2 - P) = k_1 \cdot (P_2 - P)$$

$$S_1 = \frac{\pi}{4} \cdot d_p^2$$

$$S_2 = \frac{\pi}{4} \cdot \left(d_p^2 - d_t^2\right)$$

$$S_t = \frac{\pi}{4} \cdot d_t^2$$

In these conditions, equation (1) can be written:

$$\frac{dv}{dt} = \frac{1}{m_r} \cdot \{(S_1 + k_1) \cdot P - [(S_2 + k_1) \cdot P_2 + S_t \cdot P_0 \cdot + F_u]\} \tag{2}$$

where:

$$\frac{\mathrm{dy}}{\mathrm{dt}} = \mathrm{v} \tag{3}$$

b. The pressure P differential equation is given by:

$$\frac{\mathrm{dP}}{\mathrm{dt}} = \frac{\chi \cdot \mathrm{R} \cdot \mathrm{T_a}}{\mathrm{V_0} + \mathrm{S_1} \cdot \mathrm{y}} \cdot \dot{\mathrm{m}} - \frac{\chi \cdot \mathrm{P} \cdot \mathrm{S_1}}{\mathrm{V_0} + \mathrm{S_1} \cdot \mathrm{y}} \cdot \mathrm{v} \tag{4}$$

where:

$$\dot{\mathrm{m}} = \frac{\mathrm{K} \cdot \mathrm{P_a} \cdot \mathrm{S_n}}{\sqrt{\mathrm{T_a}}} \cdot \mathrm{N}\left(\frac{\mathrm{P}}{\mathrm{P_a}}\right) \tag{5}$$

$$\mathrm{N}\left(\frac{\mathrm{P}}{\mathrm{P_a}}\right) = \begin{cases} 1 & \text{if } \ 0 \le \mathrm{P}/\mathrm{P_a} \le 0{,}528 \\ \mathrm{a} \cdot \left[\left(\frac{\mathrm{P}}{\mathrm{P_a}}\right)^{\frac{2}{\chi}} - \left(\frac{\mathrm{P}}{\mathrm{P_a}}\right)^{\frac{(\chi+1)}{\chi}}\right]^{\frac{1}{2}} & \text{if } \ \frac{\mathrm{P}}{\mathrm{P_a}} > 0{,}528 \end{cases} \tag{6}$$

where the coefficients are given by [1]:

$$\chi = 1{,}4\ [-]$$

$$\mathrm{R} = 287.04 \left[\frac{\mathrm{m}^2}{\mathrm{s}^2 \cdot \mathrm{K}}\right]$$

$$\mathrm{K} = 0.04042 \left[\frac{\sqrt{\mathrm{K}} \cdot \mathrm{s}}{\mathrm{m}}\right]$$

$$\mathrm{a} = 2.6143\ [-]$$

When functioning, the following cases can be found:

1. If $R = (S_1 + k_1) \cdot P - [(S_2 + k_1) \cdot P_2 + S_t \cdot P_0 + F_u] < 0$ than the displacement $y = 0$ and a filling process of a fix volume V_0 takes place, which produces the increase of the pressure in this volume to the value:

$$P_{lim} = \frac{(S_2 + k_1) \cdot P_2 + S_t \cdot P_0 + F_u}{S_1 + k_1} \tag{7}$$

In these conditions the speed $v = 0$, and the pressure differential equation (4) becomes:

$$\frac{dP}{dt} = \frac{\chi \cdot R \cdot T_a}{V_0} \cdot \dot{m} \tag{8}$$

The initial pressure in the volume V_0 is the atmospheric pressure.

1.1. First, the flowing regime through the nominal area S_n of the control valve DP_a is a sonic one, according to the pressure ratio value: $P \le 0.528 \cdot P_a$. In this case, the mass flow rate is given by:

$$\dot{m} = \frac{K \cdot P_a \cdot S_n}{\sqrt{T_a}},$$

and the pressure differential equation becomes:

$$\frac{dP}{dt} = \frac{\chi \cdot R \cdot T_a}{V_0} \cdot \frac{K \cdot P_a \cdot S_n}{\sqrt{T_a}} = c_1 \cdot P_a \tag{9}$$

where:

$$c_1 = \frac{\chi \cdot R \cdot \sqrt{T_a} \cdot K \cdot S_n}{V_0} \, [s^{-1}]. \tag{10}$$

Integrating equation (9) the pressure is obtained:

$$P = c_1 \cdot P_a \cdot t + c_2$$

The integration constant c_2 is found from the condition that at $t = 0$ the pressure in the volume V_0 is $P = P_0$ and its value is $c_2 = P_0$.

So, the pressure is given by:

$$P = c_1 \cdot P_a \cdot t + P_0 \tag{11}$$

The pressure in the volume V_0 will reach the critical value $P_{crt} = 0.528 \cdot P_a$ (corresponding to the end of the sonic flowing regime) at the time:

$$t_{crt} = \frac{0.528 \cdot P_a - P_0}{c_1 \cdot P_a} \, [s] \tag{12}$$

1.2. From this point the flowing regime becomes subsonic. The equation (8) becomes:

$$\frac{dP}{dt} = \frac{\chi \cdot R \cdot T_a}{V_0} \cdot \frac{K \cdot P_a \cdot S_n}{\sqrt{T_a}} \cdot a \cdot \left[\left(\frac{P}{P_a} \right)^{2/\chi} - \left(\frac{P}{P_a} \right)^{(\chi+1)/\chi} \right]^{1/2}$$

This equation can be written as:

$$\frac{dr}{dt} = c_3 \cdot \left[r^{2/\chi} - r^{(\chi+1)/\chi} \right]^{1/2} \tag{13}$$

where:

$$c_3 = \frac{\chi \cdot R \cdot \sqrt{T_a} \cdot K \cdot S_n}{V_0} \cdot a = c_1 \cdot a \tag{14}$$

$$r = \frac{P}{P_a}$$

Equation (12) can be written:

$$\frac{dr}{r^{1/\chi} \cdot \sqrt{1 - r^{(\chi-1)/\chi}}} = c_3 \cdot dt$$

Using the substitution $1 - r^{\frac{(\chi-1)}{\chi}} = z^2$ the equation can be integrated and the solution is given by:

$$z = -\frac{\chi-1}{2\cdot\chi}\cdot c_3\cdot t + c_4,$$

from which the value of the pressure is obtained:

$$P = \left[1-\left(c_4-\frac{\chi-1}{2\cdot\chi}\cdot c_3\cdot t\right)^2\right]^{\frac{\chi}{\chi-1}}\cdot P_a \qquad (15)$$

The constant$c_4$is obtained from the condition that at $t = t_{crt}$ the pressure in the volume V_0 is $P = P_{crt}$ and its value is given by:

$$c_4 = \sqrt{1-0.528^{\frac{\chi-1}{\chi}}} + \frac{\chi-1}{2\cdot\chi}\cdot a\cdot\left(0.528-\frac{P_0}{P_a}\right) \qquad (16)$$

The pressure P has the valueP_{lim}at $t = t_{lim}$. Imposing the condition for these values to check the equation (15), the equation of $t_{lim}$is obtained:

$$t_{lim} = \frac{2\cdot\chi}{(\chi-1)\cdot c_3}\cdot\left[c_4-\sqrt{1-\left(\frac{P_{lim}}{P_a}\right)^{\frac{\chi-1}{\chi}}}\right][s] \qquad (17)$$

2. If $R > 0$ then the mobile assembly moves and a filling process of a variable volume *V* takes place. In this case the dynamic behavior of the system is described by the mathematical model consisting of equations (2), (3), (4), (5) and (6).

The numerical simulation of the system functioning was performed using Matlab Simulink.

3. The following constructive and functional parameters values where imposed:

$d_p = 40\ [mm]$, $d_t = 28\ [mm]$, $b_p = 4\ [mm]$, $l_0 = 20\ [mm]$, $\mu = 0{,}3[-]$, $F_u = 100\ [N]$

$d_n = 3\ m[m]$, $P_a = P_2 = 4\ [bar]$, $T_a = 293{,}15\ [K]$.

The programmed position value was imposed$y_p = 200\ mm$.

Figure 3 shows the simulation model. Running the model, the following characteristics were obtained:

- $P = P(t)$ – figures 4a and 4b;
- $y = y(t)$ – figures 4c and 4d;
- $\dot{y} = \dot{y}(t)$ – figures 4e and 4f.

The effective start moment is$t = t_{lim} = 0.0102$ s, as shown in the diagrams from figures 4.a, 4.c and 4.e. In this moment the pressure in the chamber becomes $P = P_{lim} = 3.5\ bar$.

When the distance to the programmed position reaches a pre-settled value, the command of the control valve DP_a is cancelled, the air supply of the volume *V* stops, and the mobile assembly continue to move due to the inertia.

The speed of the mobile assembly decreases to the value$v = v_f = 0.1 m/s$. When the condition$y \geq y_p - \varepsilon$is fulfilled, the movement stops, due to a braking system (not discussed until now).

 DOI: 10.1051/matecconf/201712108001

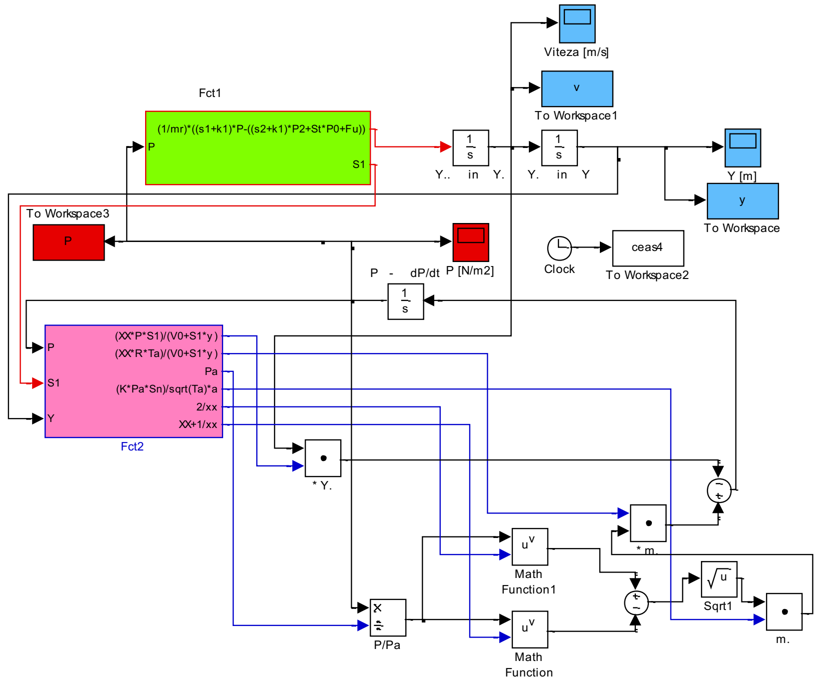

Fig. 3. The simulation model.

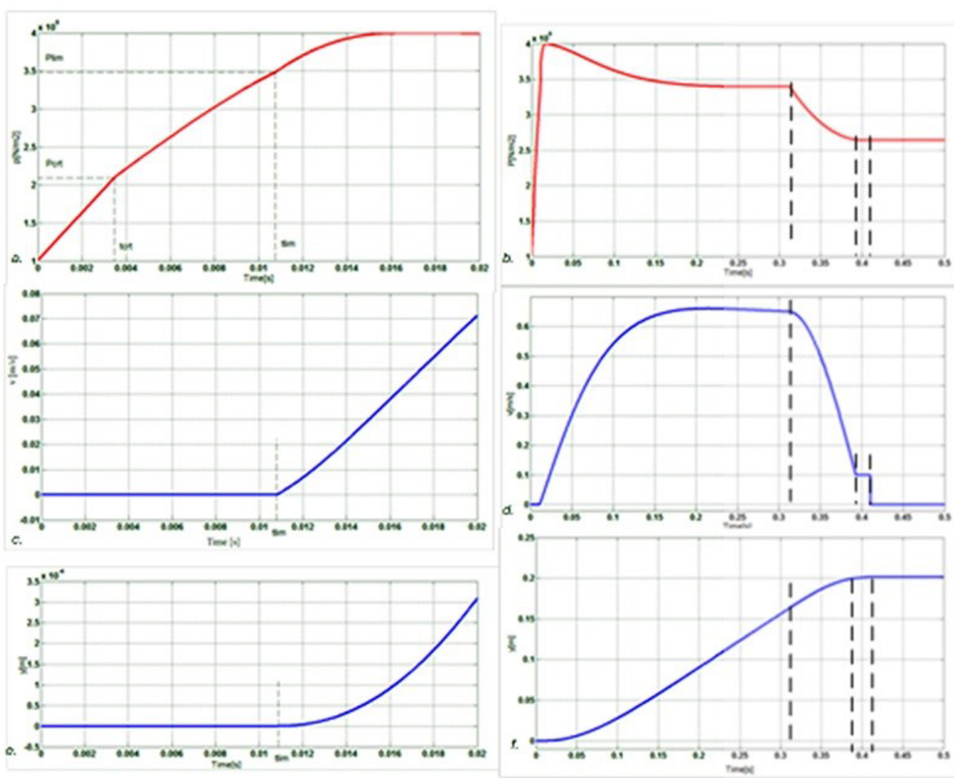

Fig. 4. The characteristics obtained by running the model.

4 Conclusions

The proposed pneumatic linear actuator allows the positioning of a pay load in any point of the working stroke with an imposed accuracy. The structure of the actuator is original, very simple, using common devices, most of them being standardized. Using two 2/2 control valves, "all or nothing" electrically controlled, an accurate control of the pressure in the working active volume can be obtained and the desired position can be reached.

The theoretical analysis of the system, performed on the basis of the developed mathematical model, confirmed the anticipated behavior of the actuator, according to the results obtained by integrating the model using the graphical programming environment Matlab Simulink.

The future approach will be the construction of the experimental model of the actuator. The command system will use a microcontroller and the working programs will integrate different variants of command and control algorithms. The results will be presented in a future paper.

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