

# Research on the designing of pneumatic positioning units controlled with valves commanded in modulated pulses

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**Abstract.** This article presents the hardware structure for a new type of closed loop positioning system using pneumatic energy. In brief, when the mobile subassembly of the system is about to reach a targeted position its speed is controlled by the small-sized pneumatic electro valves, which are commanded in modulated pulses. Here, we developed an electronic control system of which memory has a specially designed algorithm. In addition, the pneumatic engine has a specific construction that integrates a transducer of position as well as a braking system. The proposed mechatronic system is described by good positioning accuracy and low cost.

## 1 Introduction

A positioning system must be capable of translating or rotating a certain load, with a controlled speed, to position it with a certain error anywhere on the working stroke and, additionally, to preserve this position in time.

These types of systems can be operated electrically, pneumatically or hydraulically. The choice has to be made based on the type of the application they are meant for and on a technical-economic analysis. For applications where small and medium loads are involved, hydraulic drives are excluded because they are only justified where high forces and moments are needed. For tasks involving low and medium value loads, the other two options remain in place. Choosing one method over the other depends on the at the designer's preferences. Furthermore, it is necessary to found less costly, energy-efficient solutions that lead to higher positioning precision.

The electric drive might meet these requirements. However, in the long run, certain aspects of this type of drive can lead to high costs due to the problems that might arise during operation. As a first example, components of an electrical drive system can heat up and suffer behavioral changes due to high temperature. [1] This requires a significant cooling time. In fact, low-cost systems are often only capable of operating at 50% of the work cycle, having

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a resting time as long as they are in operation. Pneumatic positioning systems, on the other hand, do not contain mechanical equipment or components that can overheat. This allows a 100% work cycle.

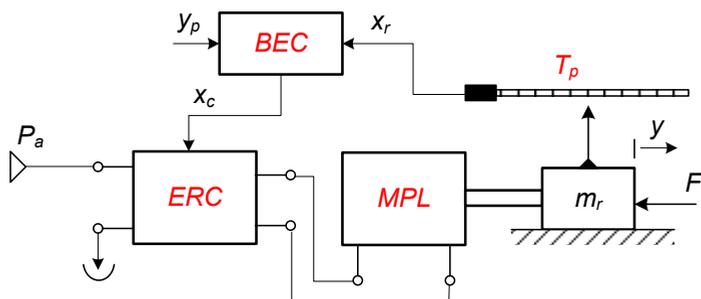
At the same time, pneumatic positioning systems are more energy efficient. It is known that in the case of electric drives the maintenance of the position implies an energy consumption. When they are not powered up, these systems reset, thus losing the position, which puts its mark on the productivity that will suffer from this cause. Instead, pneumatic systems do not have this problem. These systems have in their construction a component which, in the programmed positions, interrupts the flow of air in both directions, thus blocking the mobile subassembly of the engine.

In conclusion, in the event of an accidental interruption of a power supply, it is much easier to resume operation with a pneumatic positioning system. Moreover, the pneumatic components are quite economical and easy to repair. When pneumatic cylinders are broken or worn, they can be repaired or replaced at a low cost. On the other hand, when an electromechanical system has problems, it often requires a costly new driver.

## 2 Identification of hardware structures of pneumatic positioning systems

A study on this type of drive systems reveals that an ideal configuration for the structure of a positioning system cannot be identified.

The basic structure of such system (Fig. 1) includes: linear pneumatic motor - MPL, classical and proportional flow/pressure regulation and control components- ERC, a position transducer required to close the position loop -  $T_p$  and an electronic control block - BEC.



**Fig. 1.** Schematic diagram of a pneumatic positioning system

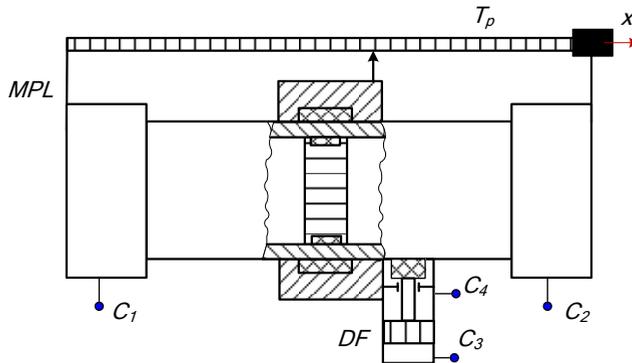
Other parts that are designed to preserve the position of the system or to compensate for the positioning error of the system can be added such as transducers of position, temperature, force, pressure, flow etc.

It should be noted that the engine construction is often special [2], rod-free, with a load-guiding system. In some situations, the motor may be provided with a mechanical brake necessary to preserve the position of the mobile subassembly after reaching the target position. Also, the position transducer can be integrated into its construction (Fig. 2).

By using a special linear pneumatic motor, a number of advantages are obtained, among which:

- the active surfaces of the pneumatic engine are equal, which makes it possible to switch off the mobile subassembly by simultaneously supplying the two engine chambers with air at the same pressure;

- the presence of the braking system allows the mobile unit of the pneumatic engine to be locked at the programmed position and to preserve it;
- a system with this type of engine can be set up with either discrete or proportional control equipment;
- by including the position transducer in the engine construction, the system structure is simplified; the mate of the transducer with a mobile subassembly is provided by the manufacturing company and it is possible to easily set a reference position;
- the absence of the rod leads to a significant reduction in the axial dimension of the system and allows for a compact guidance system to be integrated.



**Fig. 2.** Schematic diagram of a linear special-construction pneumatic motor

However, the use of this cylinder involves a high cost of application and by using the mechanical solution for braking the mobile subassembly reduces the lifetime of the system.

The block of control and regulation components – ERC - must perform the following functions:

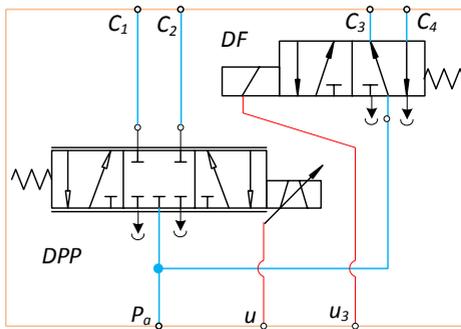
- ensure the movement of the engine driven load in the desired direction;
- provide the desired speed law by flow control;
- stop the load in the desired position; for this, either the active chambers of the engine must be blocked, or they must be supplied with air at the same pressure;
- allow control of the pressures in the active chambers of the engine.

Below are several types of diagrams for this block:

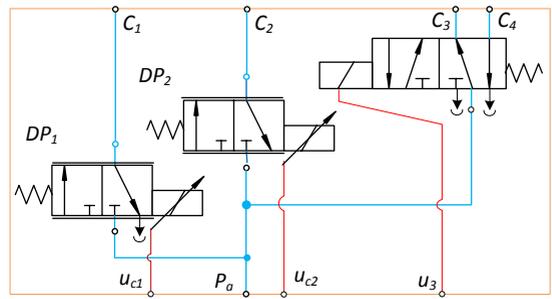
### ***Type 1***

In this case, the ERC block is formed by a 5/3 proportional solenoid valve – DPP (fig.3) and the classic 5/2 braking valve - DF, or from two 3/2 proportional valves – DPP<sub>1</sub> and DPP<sub>2</sub>, one for each engine circuit (fig.4) and the classic 5/2 braking valve.

This equipment performs the functions a, b and c. Unfortunately, today's proportional equipment is expensive and this is why systems of this type are less common.[3] This would be the reason why we are trying to develop new structures based only on classical equipment, whose price is affordable.



**Fig. 3.** Control with one proportional valve



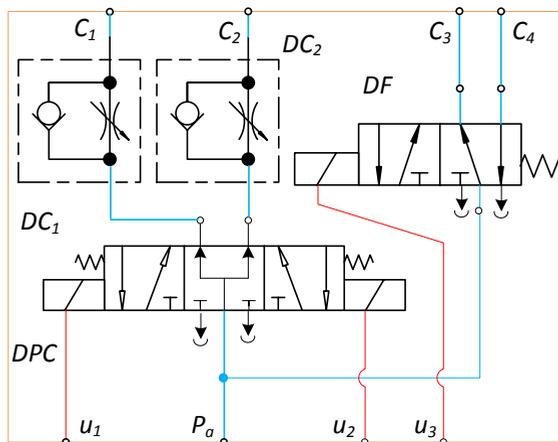
**Fig. 4.** Control with two proportional valves

### Type 2

Figure 5 shows an ERC block developed by SMC which has been able to integrate this block into a positioning system that allows loads with an error of  $\pm 0.1\text{mm}$  to be placed. [4] The functional block diagram contains the following:

- one classic 5/3 solenoid valve – DPP, with preferential position;
- one classic braking valve – DF;
- two flow speed controllers – DC<sub>1</sub> and DC<sub>2</sub>.

The working program, loaded in the memory of a controller dedicated to this type of system, materializes a special control algorithm which allows positioning of the linear pneumatic motor subassembly with the required error.



**Fig. 5.** Control with classic components

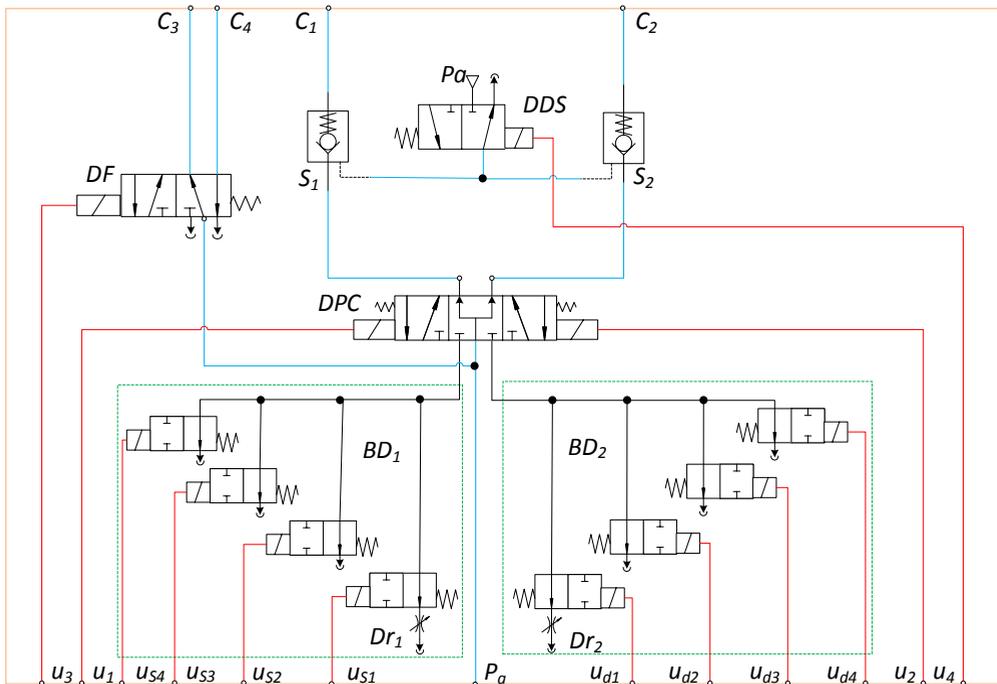
### Type 3

The block shown in figure 6 has a more complex hardware structure, containing:

- one classic 5/3 solenoid valve – DPP;
- one classic braking valve – DF;
- two air operated check valves S<sub>1</sub> and S<sub>2</sub>;
- one classic 3/2 electro valve DDS with the role of unlocking the check valves;
- 4 pieces 2/2 electrovalves block BD<sub>1</sub> and BD<sub>2</sub>; this set controls the exhaust flow from the active chambers of the engine;
- two flow speed controllers Dr<sub>1</sub> and Dr<sub>2</sub>.

With this kind of block, a stepwise speed control of the mobile subassembly can be achieved, its value being maximal when the exhaust valves are not actuated. The minimum speed is obtained when the last valve in block is not powered on and depends on the flow section initially adjusted on the flow speed controller. In order for the position to be preserved during the stopping period, the active chambers should not communicate with each other or with the atmosphere. Due to the clearance on the joint of the system, the above condition is difficult to achieve. Having these rooms locked can be achieved by the use of air operated check valves. [5]

Also, in this case, the working program stored in the memory of the electronic control unit follows a specially designed control algorithm.



**Fig. 6.** Exhaust flow control with mini valves

There is also the possibility of proportional control of the air pressure over the flow control. AVENTICS has developed a system of this type that will be presented below.

The proposed ERC block is shown in Figure 7 and contains two proportional pressure regulators RP1 and RP2 mounted on the two circuits connecting the active chambers of the pneumatic cylinder (fig. 1) with the C1 and C2 ports of the block. One of the regulators maintains a constant pressure into the active room where it is connected while the second one controls the pressure into the other room and thereby moves the mobile subassembly one way or the other.

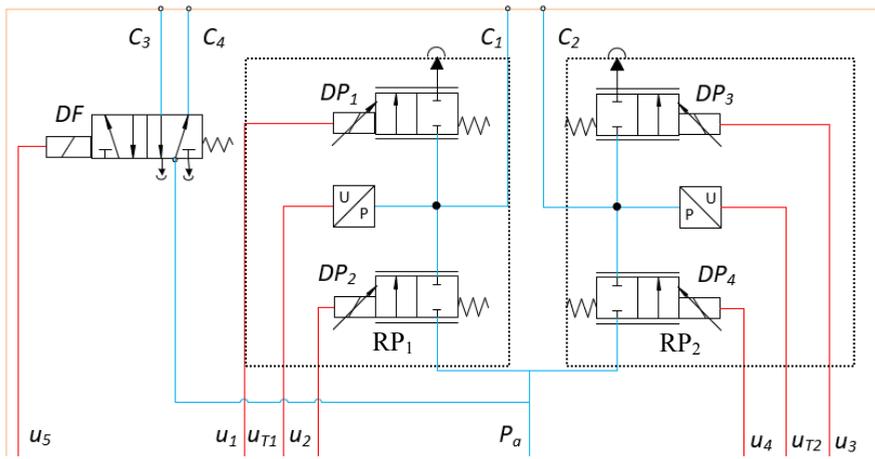
The electronic control block receives data from a position transducer and sends analog control signals to the two pressure regulators. At this time the target position is compared to the actual position to obtain the pressure ratio of the two active chambers. A control loop with a PID controller sends an analog control signal to the second proportional pressure regulator to adjust pressure as needed.

The main advantage of this method is good positioning accuracy and the fact that various types of pneumatic engines can be used in the positioning system structure. Therefore, there is a greater flexibility in designing such positioning systems.

We may have to considered that each engine has different physical characteristics. Therefore, it is difficult to make a universally valid statement on accuracy positioning of these systems. However, with an appropriately chosen cylinder and a closed loop algorithm, the positioning accuracy of  $\pm 1\text{mm}$  is certainly possible. [1]

While flow-based pneumatic systems offer better positioning accuracy, pressure-based positioning systems have a number of advantages that keep them in the minds of designers and users.

Firstly, these systems use standardized components that are easy to integrate and can be quickly replaced when needed. Secondly, the electronic control block is structured around a controller that does not require complex programming. A user enters an analog position command, saving time and resources.

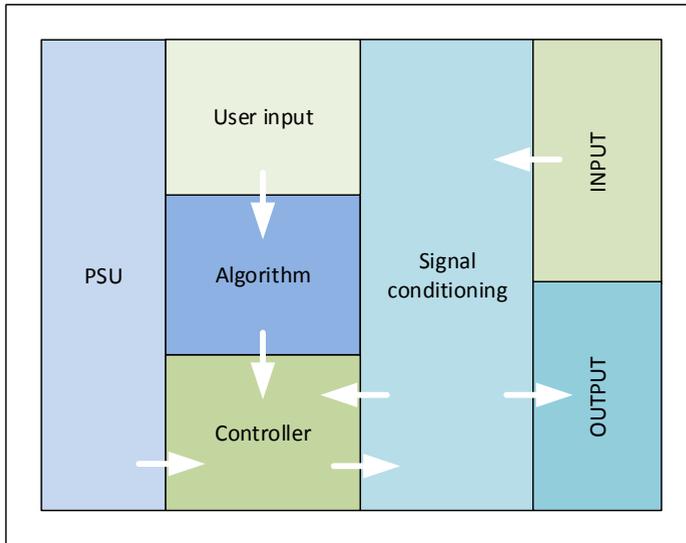


**Fig.7.** Control with pressure regulators

A particular importance should be given to the electronic control block BEC (fig.8). It integrates a controller, responsible for supervising the implemented algorithm, along with the circuits needed to adapt the input and output signals from the controller. Some of the functions of this block are:

- acquisition of signals from sensors and transducers in the system;
- control of the components based on the command algorithm specific to the type of positioning system developed;
- conversion of logic signals into power signals and reverse (in voltage or current).

The components selection of the electronic control block is determined by the components of the ERC block and the transducers used in the system - there must be a sufficient number of inputs / outputs (analogue and digital) at the controller level, as well as a sufficient number of communication ports (RS232, SPI, I2C, Ethernet, etc.). Alongside the controller, special attention should be paid to the interface used to control the electro pneumatic equipment – may need proportional amplifiers or appropriate power drivers. Although, there are also situations where the output from the controller can be directly compatible with the components used, if it includes the electronic power circuit.



**Fig. 8.** The functional diagram of the electronic control block

The control algorithm used to position the system will also be applied to the controller level. For the models presented above, the algorithm will work in a closed loop and the implementation method will depend on the chosen model. [6] Solutions that can be used include embedded systems, programmable logic controller, industrial computers, PCs and so on. Their programming can be done in a very large number of languages, depending on the platform and hardware resources - Assembly, C/C++, Python, Java, graphical languages, or high-level languages specific to a particular equipment (STL, LDR, G, etc.). Also, the combination controller-programming language will also determine the complexity of the implemented controlling algorithm.

The adjustment algorithm is of particular importance regard to achieving a certain positioning accuracy. It is always developed based on the application that it is meant for and it varies from one system to another. Most control algorithms are based on closed loops with different types of regulators such as PID, Fuzzy controllers, the implementation of neural networks - machine learning, etc. [7-8]

### 3 Presentation of proposed hardware structures and positioning systems

The solution proposed by the authors is presented below. In order to develop a system corresponding to the schematic diagram presented in figure 1, the following selections were made:

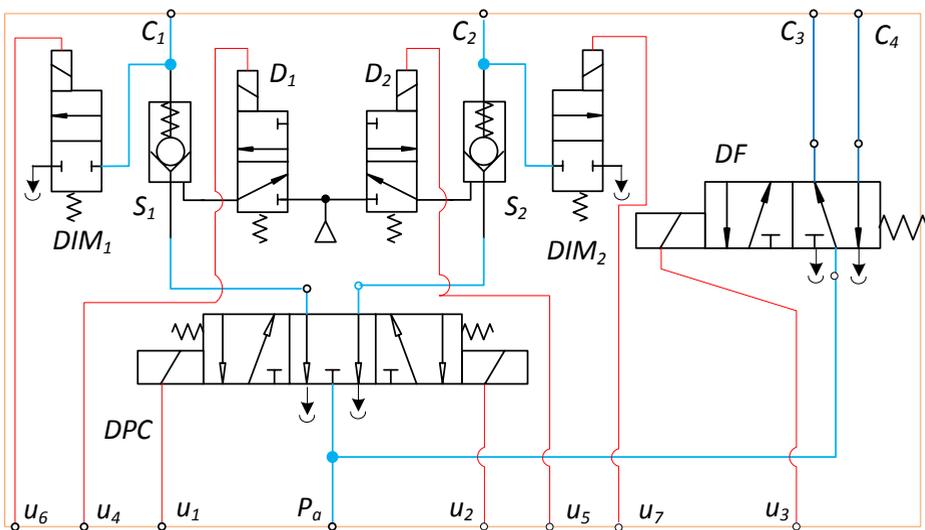
- the linear pneumatic cylinder has a special construction, with the position transducer and braking system integrated as shown in figure 2;
- ERC block is an original approach and it is shown in figure 9
- the electronic control block with a particular developed algorithm based on PWM pulses

The ERC block includes the following:

- one classic 5/3 pneumatic solenoid valve, preferential position (open center); this part ensures reversing the movement of the load and discharge the active chambers into the atmosphere when it is preferential position

- one classic 5/2 braking electro valve with spring return – DF; this part ensures that the brake is locked / unlocked;
- two air operated check valves  $S_1$  and  $S_2$ ;
- two pneumatic 3/2 classic valves  $D_1$  and  $D_2$  that operate the check valves;
- two 2/2 electro valves  $DIM_1$  and  $DIM_2$  ordered in modulated pulses.

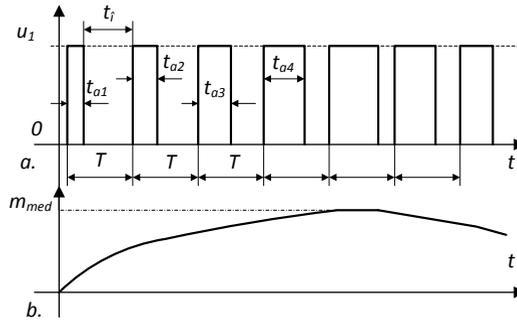
The novelty of this structure is represented by modulated pulse-controlled electro valve. They are electrically operated, have a preferential position, and their operation mode is the "all or nothing" type. In this case, the mobile element of the valve performs the opening and closing of the internal circuit with a high frequency ( $\approx 200$  Hz). In this way, the air flow obtained at the exhaust port corresponds to the average flow rate of the actual flow through the internal circuit of the equipment. It should be noted that such valve does not allow to control the instantaneous flow permanently, but an average flow control can be achieved.



**Fig. 9.** Diagram of ERC block

Flow control is achieved by appropriate command techniques. The main advantages of using these electro valves are: high response speed, acceptable cost price (the equipment is simple to construct and do not require special conditions of execution and assembly), eliminating hysteresis and its unwanted effects, achieving a very good repeatability. A drive system that integrates this type of ERC block can be controlled by a programmable controller and greatly simplifies the structure of the command system.

Two control methods for these devices are known: Pulse Frequency Modulation (PFM) method and Pulse Width Modulation (PWM) method. The first method, PFM, is less used due to the complexity of the command system. The second method, PWM, involves the use of rectangular shape pulses with constant frequency and variable width. The flow adjustment is made by changing the amount of drive time (fig.10)



**Fig. 10.** PWM control method

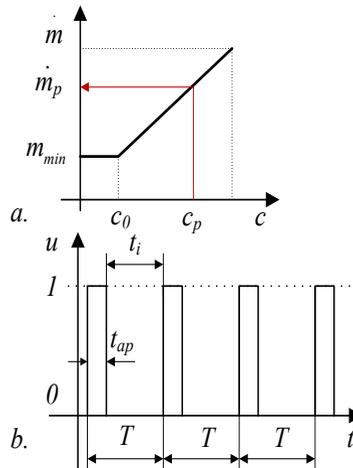
A *c* ratio can be defined as follows:

$$c = \frac{t_a}{T} \tag{1}$$

which in a first approximation can be considered to vary within the range [0,1]. Because the drive time cannot be lower than a limit value  $t_{a,lim}$ , which is the time it takes for the mobile component to perform the opening stroke, as a consequence

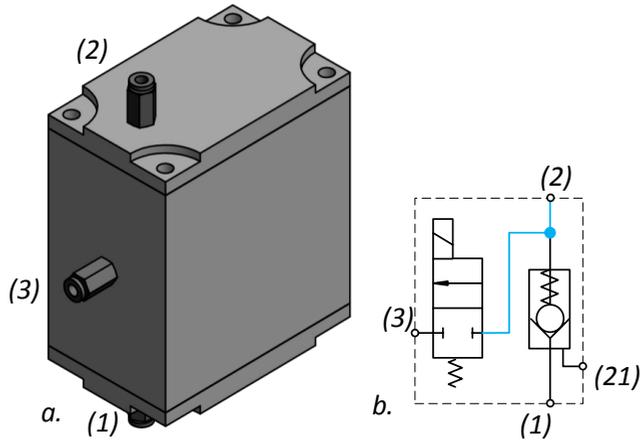
$$c \in [c_{min}, 1] \text{ where } c_{min} = \frac{t_{a,lim}}{T} \tag{2}$$

In this case, setting a value for the output flow means to program a digital signal, which greatly simplifies the command system. Therefore, we can define a variable *cp* (fig. 11b) as corresponding to a driving time tap with the desired flow  $\dot{m}_p$  (fig.11a). [9-12]



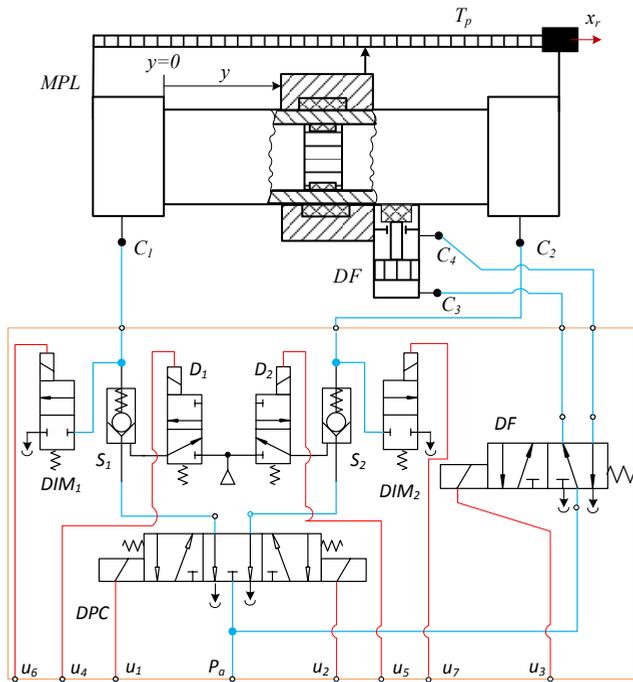
**Fig. 11.** The influence of ratio *c*

Using a 3D modeling software, the authors designed a device (fig. 12a) which is equivalent to the block formed of the air-controlled check valve and the modulated pulse-controlled electro valve. The symbol of this equipment is shown in figure 12b.



**Fig. 12.** 3D model of new equipment and diagram block

Figure 13 shows the pneumatic positioning system proposed by the authors.



**Fig.13.** Proposed positioning system

The algorithm for the system is shown in figure 14 and contains the following variables:

- $y$  - the current position of the mobile subassembly
- $y_f$  - the position for starting braking phase
- $\varepsilon$  - the requested error
- $\varepsilon_r$  - the positioning error obtained
- $i_i$  - number of trials

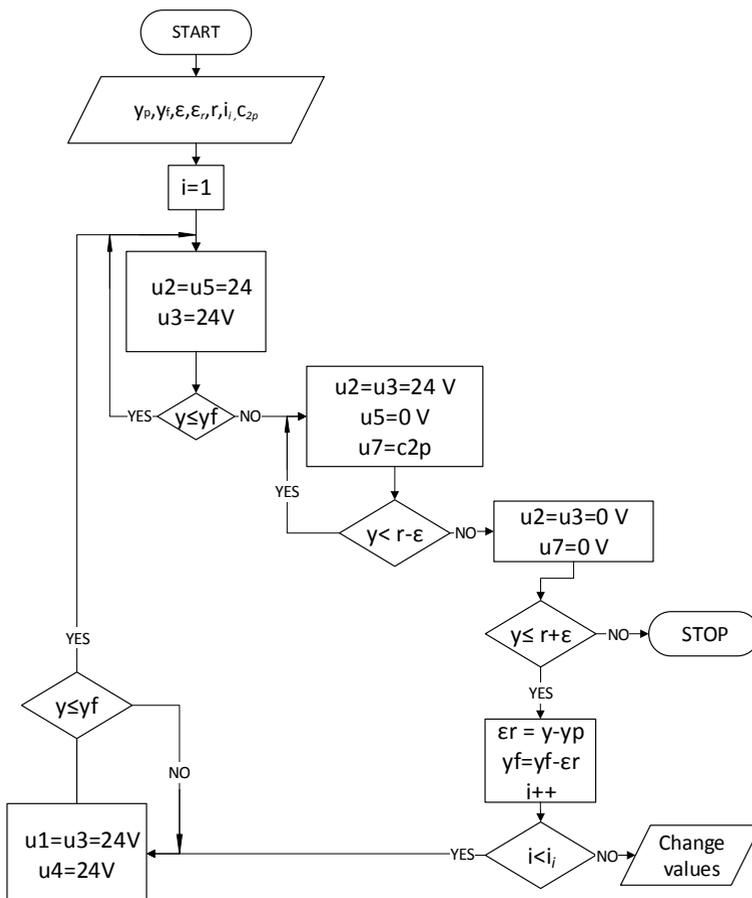
- $r$  – requested position
- $c_{2p}$  – the valve's command DIM2; it has been assumed that the mobile subassembly moves to the right.

The system will attempt to achieve requested position  $r$  with the required error  $\varepsilon$  by performing a number of attempts  $i_i$ . In the initial position (the mobile assembly is fully withdrawn to the left), all voltages are zero, so all the valves are in the preferential position.

First, the fast displacement ( $AR$ ) will take place from zero to the braking position  $y_f$ . After that, the movement continues at low speed ( $AL$ ) determined by the  $c_{2p}$  command. The DMI2 electro valve controls the exhaust flow. It closes and opens at high frequency, due to the PWM command, until the mobile subassembly reaches the target position.

If the positioning is not performed with the required error, the actual error  $\varepsilon_r$  is calculated and the mobile subassembly returns with maximum speed ( $RR$ ) to  $y_f - \varepsilon_r$  position. It will start agint the braking phase with a new braking position with a slow advance ( $AL$ ) determined by the  $c_{2p}$  command:

If the positioning is not achieved after  $i_i$  trials, a message will be displayed to the operator to change the value of  $c_{2p}$ .



**Fig. 14.** The command algorithm

## 4 Conclusions

The proposed pneumatic positioning system is a mechatronic system with a new hardware structure and a specially designed command algorithm. The system should be able to position loads with a certain error due to the special configuration of the ERC block. The presence of check valves in the system facilitates control of the fluid flow path and helps maintain the position over time. Thanks to 2/2-way electro valves, capable of repeated openings and closures at high frequencies, it is possible to control the average flow of air passing through the equipment, which allows accurate speed control and accurate positioning.

The electronic control block implemented in the system will command the pneumatic components based on the developed program that respects the algorithm shown in figure 14. The positioning process will be executed by a closed-loop control system. This is possible thanks to the position transducer which sends an analog signal to the controller, representing the actual position of the system, to close the loop.

The benefits of this solution are represented by the simplicity of ERC block, the use of classical pneumatic components, which have a low cost in contrast to the proportional equipment, and the simple and efficient control algorithm. However, a controller capable of working at high frequencies is required to order the DIM electro valves and to make corrections in a timely manner.

The proposed system is conceptual. The next step for developing this solution is to create a mathematical model of the components. Thus, some theoretical results can be obtained and a preliminary conclusion can be drawn on system performance. After developing a prototype, it is possible to compare the theoretical and practical results and to present the real performance of the system. First step in this direction was the 3D design of the new equipment incorporating the check valve S and the electro valve DIM.

In conclusion, the hardware solution, the design of the new equipment and the proposed algorithm meet the current requirements for an advanced mechatronic positioning system.

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