Trends and perspectives in proportional pneumatics

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Abstract. Trends and perspective directions in the field of pneumatic equipment and systems are first identified in the paper. Special attention is given to identifying the equipment and systems that can be adapted to the requirements imposed by a new industrial revolution - Industry 4.0. Pneumatics will continue to be an important domain and the paper presents arguments for that. The current stage of proportional pneumatics is presented and a comparison between analog and digital proportional pneumatics is made. In the final part of the paper an experimental model of a distributor controlled with modulated pulses is presented. The distributor is integrated in a system that controls the pressure in a reference volume.

1. Introduction
Pneumatic actuating systems consist of pneumatic automation equipment that generates, transmits and transforms energy, being controlled by electrical and electronic control devices. These systems are used today in a large number of applications, due to their recognized advantages such as: robustness, constructive simplicity, productivity, high reliability and, last but not least, the lower cost price. They are also used whenever the operating conditions are severe (danger of explosion, fire, humidity, etc.), or a series of hygienic-sanitary norms have to be fulfilled (food industry, pharmaceutical, nuclear technology, etc).

These systems, having a history of many years (the first compressor was invented in 1829), continued to develop, with innovative solutions being designed and launched on a regular basis. As a result, the industry of pneumatic automation equipment is constantly evolving, top companies continuing to produce increasingly efficient equipment.

The first pneumatic actuating systems had "conventional" equipment in their structure, which could control the two parameters - pressure and flow using a manual adjustment, and the electric actuating, when used, was of the "all or nothing" type. These systems offered few possibilities regarding the control of the speeds of the movable organs of the motors, their position and the developed forces and moments. This way neither the desired precision nor the speed of the actuating could be ensured, and the change of the working program of the system was difficult to be done.

These problems were overcome with the advent of proportional pneumatic equipment (after 1970). Proportional pneumatic equipment allows the parameter (pressure or flow) to be adjusted continuously, electronically, according to a preset program. This was made possible by the use of electromechanical actuators in the structure of these equipments, which in fact represent an interface between the electronic control part and the pneumatic power part.
Depending on the adjusted parameter, you can find:
- flow control equipment: proportional pneumatic drossels;
- equipment for flow direction and flow rate control: proportional pneumatic distributors;
- equipment for pressure control and regulation: proportional pneumatic valves.

An evaluation of the domain [1],[2],[5],[6],[12],[13],[14] allows the identification of the main trends and perspectives, such as:
- an important development of pneumatic in the future; for this, sustained fundamental and applied research is needed to limit the negative effects due to the physical properties of the working fluid: low viscosity and high compressibility;
- the computerization of pneumatic actuating equipment and systems; the integration of sensors (for pressure, differential pressure, flow, temperature) into their construction, the possibility of being remotely controlled, which requires the use of complex communication interfaces;
- the miniaturization and modularization of pneumatic actuating equipment and of the systems in which such equipment is integrated;
- the development of modulated pulse control techniques for controlling the on/off type distributors in order to proportionally control the flow;
- the use in the structure of power control equipment of the new types of unconventional actuators, both in dedicated structures of equipment and in new constructive solutions;
- the use of special fluids in the pilot area of proportional equipment; even though low differences of command pressures are controlled at present, a very wide range of applications will be needed in the future;
- promoting energy-efficient equipment and systems;
- promoting solutions that also take into account ecological aspects;
- at the level of the manufacturing companies, the scope to offer on the market a practically complete range of pneumatic automation equipment, covering all types and dimensions, including the related electronics, the interconnection elements, etc. (the concept of "single supplier");
- increasing the reliability, the functional accuracy and the improvement of the static and dynamic performances for the dedicated pneumatic equipment, as well as the design and development of new types of high-performance equipment.

As the fourth industrial revolution continues to grow, many doubt the future of the pneumatics. IIoT allows a higher level of personalization, precision engineering and quality management and risk assessment, with an integrated and programmable chain of activities from the beginning to the end of the production process. In addition, improved cloud connectivity, data analysis and decentralized computing lead to a fundamental change in the design, construction, operation and maintenance of pneumatic equipment and systems.

Statistics show that sales of pneumatic equipment and systems have increased considerably in the last years. At the same time, it is obvious the significant role played by the pneumatic equipment manufacturers in their innovation and adaptation to Industry 4.0; leaders such as Festo and Camozzi have introduced IIoT compatible components [3]. Sensors and cost-effective data processing systems are now integral parts of many pneumatic automation equipment.

Intelligent pneumatic drive systems were created starting from the classic systems. The basic elements around which an intelligent pneumatic system is structured are the proportional equipment. Beside these, in the structure of the system are also found: sensors and transducers, electronic circuits for signal processing, A/D and D/A converters, controllers or microprocessors [4]. Thus configured, a
pneumatic system becomes more stable, more accurate and faster, having a certain level of intelligence.

2. Current stage in proportional pneumatics
An exhaustive analysis of the achievements in the field of proportional pneumatics shows the intense activity carried out, both in terms of theoretical and experimental research for the proposed solutions, as well as regarding the company achievements. A permanent attention is given to the diversification of the products depending on the application, their miniaturization in parallel with the increase of the static and dynamic performances, the development of new equipment - based on innovative solutions - for the applications of automation (control).

Companies in the field such as Festo, SMC, ASCO JOUCOMATIC, Matrix, Burkert, Bibus, Camozzi, Tameson etc. have in their current offer high performance proportional pneumatic products. A detailed analysis of the company products is impossible in this paper; there are reference treaties that present the operating principles of proportional pneumatic products and analyze representative commercial products [7], [8].

First the pneumatic distributors will be presented from the constructive-functional point of view. To simplify, let’s consider a 2/2 distributor (with 2 positions and 2 orifices). Such equipment can be a classic one (figure 1) or a proportional one (figure 2). The most widely used constructive variant is the one with a cylindrical drawer with translational movement. The main construction elements of such equipment are: the cylindrical drawer 1, the body 2, the electromagnet 3, the elastic element 4 and the non-metallic sealing elements (in the classic version) 5.

It can be observed that, from the constructive point of view, there are no significant differences between the two variants.

![Figure 1. Classic pneumatic distributor (main presentation).](image1)

![Figure 2. Proportional pneumatic distributor (main presentation).](image2)

However, two issues stand out, namely:
- the electromechanical actuators are different - in the classic version an ordinary electromagnet of the "all or nothing" type, and in the proportional version a proportional one, analogically controlled;
- the existence of non-metallic sealing elements in the case of the classic variant, which complicates the construction, introduces large frictional forces, is worn out in time.

During operation the drawer 1 can occupy:
- only two positions (the preferred position and the controlled position); in this case, the control voltage can have only two values \( u_c \in \{0, u_c\} \), and the flow section through the equipment will be zero or it will have the nominal value \( S_c \in \{0, S_n\} \); consequently, at the outlet orifice of the
distributor the flow rate may be zero or the nominal value, therefore \( \dot{m}_2 \in [0, \dot{m}_n] \); this is the case of the classic distributors - figure 1;
- any position on the stroke; in this case the control voltage can have any value in the range \( u_c \in [0, u_n] \), and the flow section through the equipment will correspond to the control voltage, having a value in the range \( S_c \in [0, S_n] \); consequently at the outlet orifice of the distributor the flow may have any value in the range from zero to the nominal flow, therefore \( \dot{m}_2 \in [0, \dot{m}_n] \); this is the case of proportional distributors - figure 2.
So, the characteristic of the electromechanical actuator influences the control characteristic of the equipment.

Two further aspects must be mentioned:
- in the case of the classic distributors, the functional play between the drawer and the body usually has values in the range 6 ... 8 \( \mu \text{m} \), and the coverage length, defined as \( l_a = (L - l)/2 \) can take values in the range 2 ... 4 mm;
- in the case of proportional distributors, the functional play between the drawer and the body usually has values in the range 1 ... 2 \( \mu \text{m} \), and the coverage length, defined as \( l_a = (L - l)/2 \) can take values in the range 10 ... 20 \( \mu \text{m} \);

The last-mentioned aspect shows that, in the case of proportional distributors, more difficult problems arise in terms of manufacturing and assembly. For these reasons there are few companies producing such equipment nowadays, and the purchase price for such equipment is high. In addition, an electronic amplifier with a special structure is required to control the equipment, which doubles the purchase price.

In conclusion, the analogical proportional equipment is expensive, they have - in general - a hysteresis of high values, the characteristic can have areas with different slopes, the performances are given by the manufacturing precision of the constructive elements of the equipment, by the mechanical friction, by the existing plays, by the existence or absence of automatic control of the actuator's mobile armature position. For these reasons, the control systems for such equipment are complex and expensive. Therefore, to reduce the hysteresis, Dither generators and the position feedback at the level of the mobile armature are used.

This is why new solutions, accessible for a wide range of users are searched. For the control of the flow, modulated pulses-controlled equipment can be used.

These are in fact electrically operated distributors, with preferential position; in the case of these distributors, whose symbol is shown in figure 2b, the actuation is done with a classic electromagnet, the operation of the distributor being of the "all or nothing" type.

In this situation, the mobile element produces the opening and closing of the internal circuit with a high frequency (\( \approx 200 \text{ Hz} \)). This way, at the consumer orifice (2) the obtained air flow corresponds to the average value of the actual flow that passes the internal circuit of the equipment.

It should be noted that such equipment does not allow a continuous adjustment of the instantaneous flow, but instead an average flow control is obtained. The flow modulation is obtained through appropriate control techniques.

The main advantages of using these distributors are: high response speed, acceptable cost price (the equipment is simple and does not impose special conditions of manufacturing and assembly), eliminating hysteresis and its undesirable effects, obtaining a very good repeatability. At the same time, an actuation system in which such equipment is integrated can be controlled using a microprocessor, which greatly simplifies the control system structure.

Various control techniques are based on combining the outputs of several distributors of the same kind, usually grouped into "batteries", and especially on the adjustment of the opening and closing time of the distributor section.

In order for the working frequency to be in the specified range, the movable element of the distributor must have an inertial mass as small as possible and the classical actuator can operate at these frequencies. This is why a conical or spherical valve is preferred as a moving element.
Figure 3 shows such equipment.

![Figure 3](image)

**Figure 3.** The principle diagram of a proportional distributor.

It has two sub-assemblies: the electromechanical actuator A and the base module MB. The basic module MB consists of a balanced conical valve S, whose position relative to its seat, machined in the body c, is determined by the supply voltage of the actuator, which can have only two values, zero for the preferential position and the nominal value for the commanded position. Matrix produces and commercialize such equipment. Figure 4 shows a constructive example.

![Figure 4](image)

**Figure 4.** MATRIX manufacturing proportional distributor.

In [16] these techniques are presented related to the MATRIX products. According to [16], the MATRIX switching valves have a unique and innovative technology, which means that the switching is performed without friction, and the moving part has a very small mass (figure 5). The manufacturer claims that the combination of the aforementioned processes leads to a very long lifespan (up to 4 billion changes). This reduces maintenance costs by extending the maintenance intervals of the installations [16].

![Figure 5](image)

**Figure 5.** Matrix switching valve.

Due to the frictionless mode of operation, it is possible to obtain switching times <1 ms, respectively a frequency up to 1500 Hz.
Matrix uses the concept of modular design of switching valves, reducing the workspace by arranging more devices (up to 9) in a single block. This way, a constellation of valves reduces material consumption and installation time, essentially simplifying the entire pneumatic system. It should be noted that Matrix switch valves are insensitive to acceleration and vibration.

Being digital controlled devices (On/Off), Matrix switching valves allow the following types of modulation: \textit{PWM}/Pulse-Width-Modulation (figure 6), \textit{PFM}/Pulse-Frequency-Modulation (figure 7), \textit{PNM}/Pulse-Number-Modulation (figure 8) and \textit{PCM}/Pulse-Code-Modulation (figure 9).

A combination of the four types of modulations is possible, depending on the requirements of the application.

For the control system of the Matrix switching valves Speed-Up technology is used (figure 10), which guarantees an operating time <5 ms and a reduction of energy costs with 90%.

When designing the distributors, Matrix took into account two very innovative principles, namely:
- the absence of internal friction during the opening and closing phases;
- a modular architecture, which allows the assembly of several modules in a single body.

It can be observed that the basic module MB is found in the construction of the equipment (figure 5). In addition, the following constructive elements appear:
- the plunger 2 which is in contact with the free end of the moving armature and which exerts on the armature the elastic force developed by the compression spring 3;
- the spherical contact 4;
- the body of the equipment 1, consisting of several parts, in which the orifices of the equipment are machined.

The advantages of this construction are the following:
- compactness;
- small response times;
- insensitivity to working frequency and vibration;
- low absorbed power;
- precision, repeatability and flexibility;
With such equipment, flow rates of up to 180 l/min can be controlled, and the working pressure can be controlled in the range 0 ... 8 bar. Possible applications can be listed:

- process and precision equipment;
- pressure and flow control equipment;
- positioning systems;
- sorting systems;
- measuring systems;
- biomedical and metrology equipment.

3.3. Development of an experimental model of a modulated pulses-controlled distributor

This paper aims to analyze the performance of an original proportional equipment [10], [12] ... [15], capable of achieving a proportional control of the flow.

Over time, the authors have developed several constructive variants of such pneumatic equipment [7, 8]. In this paper an experimental model was used - figure 11 - which was tested and integrated into the structure of a pneumatic system.

![Figure 11. Modulated pulses-controlled distributor:](image)

a - the principle diagram; b - symbolic representation; c - the physical model

The main constructive elements of this equipment are: the body 1, the spherical valve 2, the movable armature 3 and the electromagnet 4.

This equipment is integrated into a system that aims to maintain the pressure between two limits (two-position adjustment) in a tank with variable losses.

Essentially, the proposed system aims to regulate the pressure inside a fixed volume reservoir $V$ at the desired value $P_n$ and to maintain it constant within reasonable limits (below 10%). The functional scheme of the system is shown in figure 12.

From a compressed air source $S$, a pressure up to 8 bar is applied through a manual valve $R$; using the manual pressure regulator $RP$ an input value of the pressure is obtained, higher than the nominal pressure $P_n$ (15% -20% higher than the desired value).

The $DIM$ modulated pulse distributor is controlled - through the CEC electronic circuit - by the program developed in LabVIEW 2011 environment and the connection module with the external environment NI USB-6001.

The frequency of the control pulses is measured with the digital oscilloscope OD (the second channel of the oscilloscope is used for the negated signal to see the correspondence with the front panel of LabVIEW).
Figure 12. The functional diagram of the automatic pressure control system.

The distributor supplies the constant volume tank, its output being applied to a TP pressure transducer. Also, by means of a fork, a manually adjustable fluid loss is simulated, the flow of which is measured with the flow transducer Tq.

Within the program developed in the LabVIEW 2011 environment (academic license), the control impulses for DIM, the acquisition and display of signals from pressure and flow transducers (analog components), as well as the two-position pressure control module are performed.

For the initial filling part of the tank up to the Pn value, a manual control was performed in LabVIEW, followed by an automatic order for entry into nominal operating mode.

The experiments aimed to highlight the behavior of the pulses-controlled distributor at frequency, duty cycle factor and nominal pressure.

Also, with the help of a pneumatic bi-stable (Festo), the experiments were repeated in the same manner, thus being able to draw conclusions regarding the performances and how to improve them for the pulses-controlled distributor.

4. Experimental results
An overview of the experimental setup is shown in figure 13, where the physical devices correspond to those captured in the principle diagram of figure 11.

In LabVIEW 2011 environment an executable program was developed, with the front panel illustrated in figure 14 and the block diagram in figure 15.

The experiments followed the behavior of the modulated pulses-controlled distributor related to frequency and the duty cycle factor. It was observed that, at the same value of losses, measured by the electronic flow meter, the response of the pressure regulation system is better as the duty cycle factor is higher and the frequency of the control pulses is also higher (this aspect was expected as it is in accordance with the theoretical analysis presented in [10], [12], [14], [15]).

It should be noted that the system responds correctly if the losses are lower than the average flow provided by the pneumatic pulses-controlled distributor.

In the future the authors will also experiment with other constructive-functional solutions of pulses-controlled distributors in order to obtain an optimal solution for the performance / price ratio.
Figure 13. Overview of the experimental setup.

Figure 14. The front panel of the application.
5. Conclusions
The computerization of the pneumatic drive systems marked a special qualitative leap and created the premises for the development of modern pneumatic systems. These systems contain classic and proportional automation equipment. Their main task is to carry out useful tasks, and their essence consists in being able to react intelligently to new or disruptive situations by taking appropriate decisions based on the data provided by their sensors and/or transducers systems. At the same time, they have the possibility to be remotely controlled, which requires the use of complex communication interfaces.

The arguments presented in the first part of the paper show that these systems are prepared to meet the demands imposed by Industry 4.0.

The proposed equipment model is a simple constructive one, which can successfully replace the more complex and more expensive analog proportional equipment.

Following the integration of this equipment in a pneumatic drive system and the carrying out of the experiments, a number of conclusions were drawn for the increase of the dynamic performances, as follows:

- it is necessary to use an electromagnet with a very small inertial mass in order to be able to operate at higher frequencies; for this reason, an electromagnet with oscillating armature must also be considered;
- by using a stronger spring in the return flight of the mobile system, an increase in the operating frequency was obtained;
- the response time of the equipment is reduced with the increase of the supply current of the electromagnet winding.

The experiments carried out may represent the premises for the development of proportional pneumatic equipment capable of working in high performance applications.
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