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DEVELOPMENT AND CONTROL OF CONFIGURABLE ARRAYS OF PNEUMATIC DIGITAL VALVES

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Abstract: *The paper tackles the replacement of costly proportional direction control valves by cheaper configurable arrays of digital micro valves. An original solution of such valve, developed by the authors, is used for exemplification. The micro valve is characterized by simple construction, modular structure, easy-to-implement digital control and reduced costs, features that recommend it for use in various types of applications. Control techniques that may be used are also presented.*

Keywords*: digital direction control valve, configurable valve array, PWM control*

1. Introduction

Modern pneumatic driving systems are endowed with intelligent sensors, embedded informatics and control equipment, high performance braking systems and are characterized by increased reliability, functional accuracy and static and dynamic performance as intensive research efforts are made in order to reduce the negative effects induced by the physical properties of the working fluid (such as reduced viscosity and high compressibility). In this context the authors aim to promote pneumatic actuation systems by developing original, modular structures of PWM controlled micro direction control valves able to be configured as versatile valve arrays.

Pneumatic solenoid valves may be subdivided into two categories: digital on-off solenoid valves and proportional solenoid valves. Digital solenoid valves combine their open-closed position with an electric on-off control. Proportional solenoid valves can be partially opened in direct proportion to the input signal (variable voltage or current).

The evolution of technology led to the development of new flow control techniques, which allow the use of digital components instead of proportional ones. PWM (Pulse Width Modulation), one of these control techniques, is based on the generation of a square wave of constant frequency, with variable pulse duration. The DC (duty cycle) is defined as the rate between the variable pulse duration t_p and the constant period of pulses T_o: DC [%] = t_p / T_o x 100. A linear growth of the duty cycle corresponds to a linear growth of the pulse duration. It means that a PWM control to a 2/2 normally closed (NC) solenoid valve implies a proportional variation of the passing flow rate, which results to be: $Q = Q_{nom} \times t_p / T_o$, where t_p is variable, Q is the actual passing flow rate and Q_{nom} is the rated (nominal) flow rate. The flow rate may thus assume any value between zero and the nominal flow.

The solution proposed in this paper lines up alongside with the tendencies of worldwide promotion of PWM controlled valves as quick, accurate and cheap solution with applications that range from positioning systems to biomedical engineering [1 - 8].

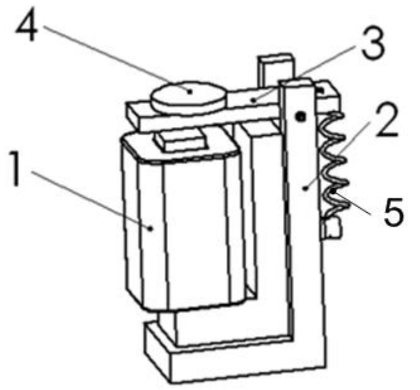
2. Previous solutions of pneumatic digital valves developed by the authors

The authors have developed a number of constructive solutions of such pneumatic devices. All the versions were elaborated complying with certain general and specific design requirements:

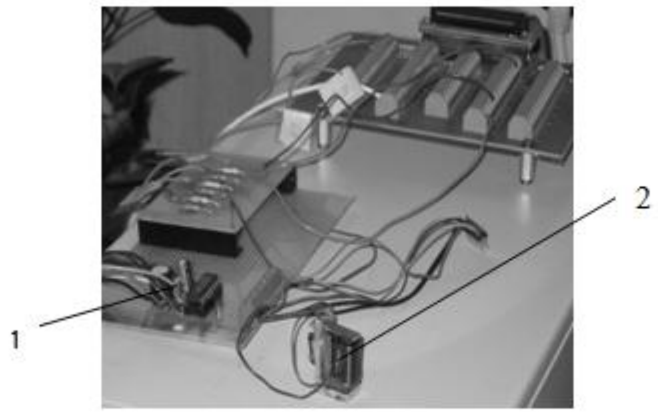
- achievement of miniature experimental models;
- use of a large number of standard or modular parts;

- manufacturing technologies specific to universal machines-tools available in Romania.

A first solution of pneumatic digital valve [9] is presented in figure 1. The main subassembly (fig. 1a) is constituted of the magnet 1, the cradle 2, the mobile plate 3 and the valve 4. When the electromagnet 1 is not excited, the valve 4 closes the way between the supply and the consumer. The helical spring 5 helps the closing. When the magnet is excited, the armature is attracted and the connection between the supply orifice and the consumer is established again.
The first solution used an electromagnet encountered in the construction of matrix printers. Meanwhile, an electromagnet designed specifically for this application was developed.



a)



b)

Fig. 1. Solution of pneumatic digital valve that features a cradle and a mobile plate; a) 3D representation of the main subassembly: 1 – magnet; 2 – cradle; 3 – mobile plate; 4 – valve; b) experimental model: 1 – electronic amplifier; 2 – pneumatic digital valve

Another example of pneumatic device that integrates a PWM controlled direction control valve is presented in [10]. Figure 2 shows a 3D representation of the solution (with the valve body removed).

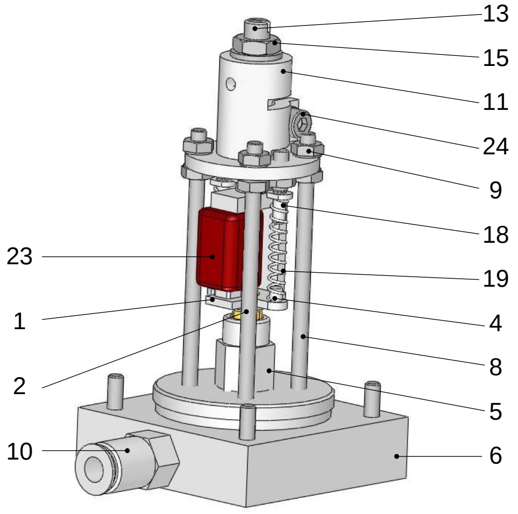


Fig. 2. Pneumatic device that integrates a PWM controlled direction control valve: 1 – mobile armature; 2 – conical seat; 3 – ball; 4 –bolt; 5 - guiding part; 6 – valve cover; 7 – coupling; 8 – tie rods; 9 – nuts; 10 – quick coupling; 11 – upper plate; 12 – adjustment rod; 13 – adjustment screw; 14 – groove; 15 – nut; 16 – collar; 18 – stud bolts; 19 - spring; 20 – valve body; 22 – clamping holder; 23 – magnet; 24 – screw.

The equipment has three positions and two nozzles, the preferential position interrupting the circuit. The flow section is of type cylindrical seat – conical valve. The conical seat 2 is guided through the part 5 where the cylindrical seat is manufactured. The mobile armature 1 is fixed to the valve 2. Two compression helical springs are used in order to preserve the preferential position. The initial rise of the springs can be adjusted with the help of the stud bolts 18. The pneumatic valve is driven using the magnet 23. There are two ways of adjusting the air gap. The coarse adjustment means moving the upper plate 11 towards the valve cover 6 using the tie rods 8 and the nuts 9. The fine adjustment uses the adjustment screw 13 and the adjustment rod 12, whose rotation is obstructed by the groove 14. The rotation movement of the screw 13 is therefore transformed in translation movement of the rod 12 fixed to the magnet. After establishing the air gap, the described assembly is locked using the screw 24. The pressure supply nozzle is materialized by the quick coupling 10 and the consumer nozzle by the coupling 7. In order to be fixed on a stand, the clamping holder 22 is assembled on the valve body 20.

3. The basic module

With a view to achieving an easy-to-configure solution, the authors focused on the developing of the core of the configurable valve array, the so-called “basic module”. The basic module is in fact an innovative construction of PWM controlled micro valve that integrates the control electronics. The micro valve is designed in a modular structure that will easily allow multiplying and combination in function of the flow rate required by the application. Identical basic modules can be configured as arrays of valves by mounting in a common body.
A section through the 3D model of the basic module is presented in figure 3.

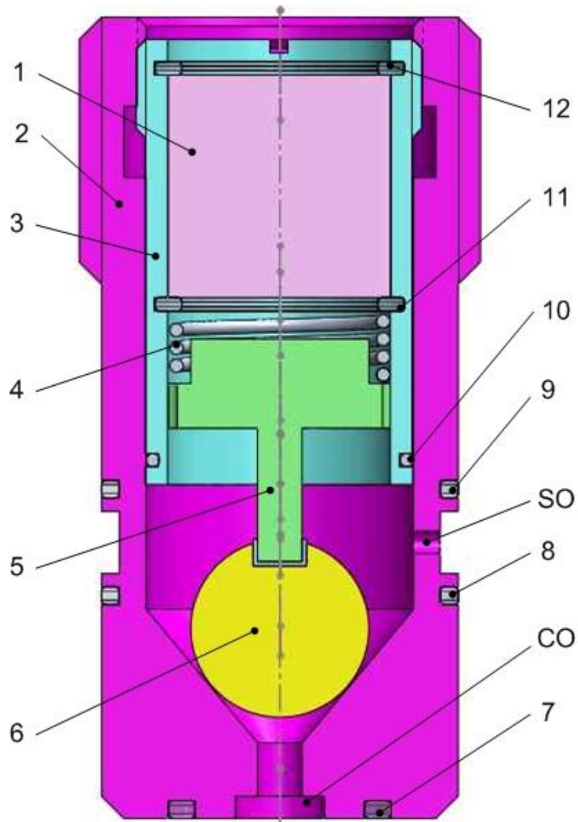


Fig. 3. Section through the 3D model of the basic module: 1 – fixed subassembly of the magnet; 2 – valve body; 3 – bushing; 4 – helical spring; 5 – mobile subassembly of the magnet, 6 – ball; 7, 8, 9, 10 – O-ring; 11, 12 – elastic ring; SO – supply orifice; CO – consumer orifice.

The innovative PWM controlled micro valve is a small sized device (d_n = 2 mm) of type 2/2 or 2/3, having a preferred position, and is electrically controlled using a magnet that can function at high working frequencies (≈ 200 Hz). Normally, the path between the supply orifice *SO* and the consumer orifice *CO* is closed by the ball 6 solidarly joined to the mobile part of the magnet 5 and

pressed by the compression spring 4. The fixed subassembly of the magnet 1 is mounted in the bushing 3 and its position is maintained by two elastic rings. The bushing 3 is fastened in the valve body 2, provided with an external screw thread for assembly purposes. The relative distance between the fixed and the mobile subassemblies of the magnet is adjusted during mounting.
An airflow is obtained this way through the consumer orifice *CO*, corresponding to the mean value of the real flow that passes through the internal circuit of the device. Besides, the valve allows the free flow of the fluid from *CO* to *SO*.
The device does not achieve a continuous control of the instantaneous flow, but controls the mean flow in direct proportion to the duty cycle. It is shown in [11] that an almost linear variation of the flow rate in function of the ball travel is obtained.
Among the advantages of the proposed solution are: reduced price compared to proportional pneumatic direction control valves, elimination of hysteresis and its bothersome effects, very good repeatability.

4. Array configuring

The main advantages of the modular solution refer to ease of mounting in a common body, rapid connection to supply and discharge, versatile configuring of various arrays of such valves. The control of significant flow rates will require the use of arrays of such micro valves since a basic module can control a flow rate of maximum 180 l/min. For instance, an array of 9 basic modules can control a flow rate of 1960 l/min at a supply pressure of 8 bar.
The micro valve was designed as modular basic module in order to easily allow multiplying and combination in function of the flow rate required by the application. Identical basic modules can be configured as arrays of valves by mounting in a common body. Figure 4 presents an example of such a valve array.

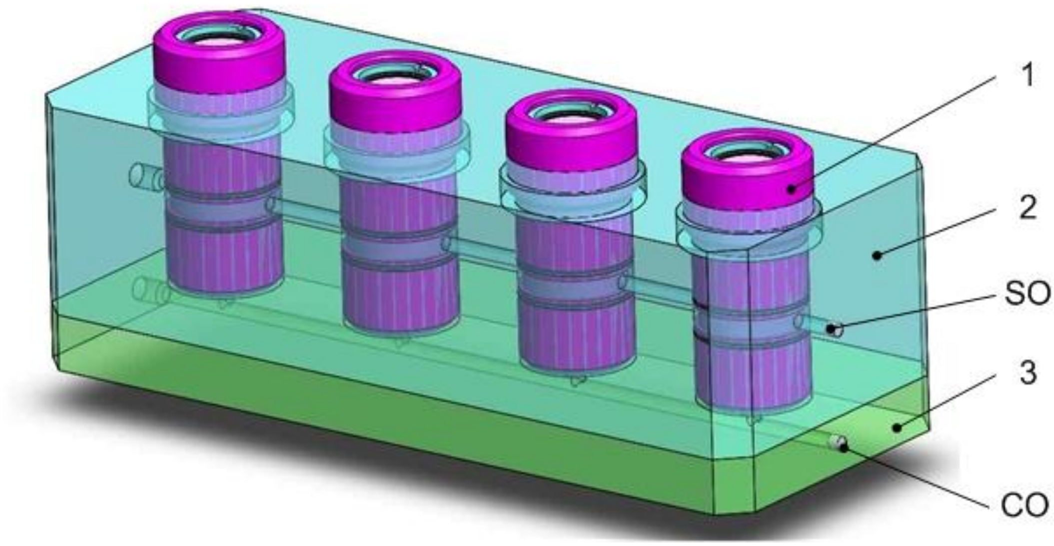


Fig. 4. Array of four PWM controlled micro valves parallelly arranged: 1 – micro valve (basic module); 2 / upper plate; 3 – base plate; SO – common supply orifice; CO – common consumer orifice

An alternate arrangement is presented in figure 5. In this case the three dimensional assembly comprises six basic modules 1 described before in order to achieve a better efficiency of the system. There is a hexagonal body 2 with six radial channels placed on each planar surface, so that the fluid with the established working pressure value is obtained along the common consumer orifice (the central hole). The process could be done for two or more basic modules, in function of the requirements of the application. Meantime, the electronic device can be controlled following the number of working micro valves.

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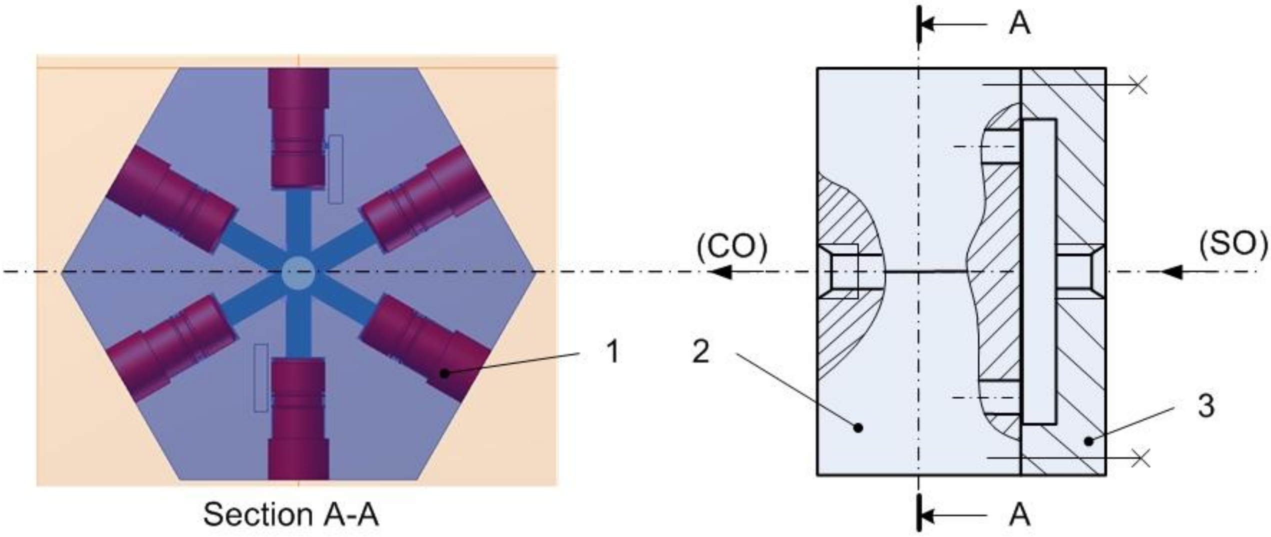

Fig. 5. Array of six PWM controlled micro valves arranged on a hexagonal body: 1 – micro valve (basic module); 2 – hexagonal front plate; 3 – hexagonal back plate; SO – common supply orifice; CO – common consumer orifice (central hole).

Another way of obtaining variable flow rates is to group arrays of valves with flow sections that observe the pattern $S_0, 2 \cdot S_0, 2^2 \cdot S_0 \ldots 2^n \cdot S_0$. In function of which magnets are supplied, 2^{n+1} distinct outputs can be obtained.

5. Control of configurable arrays of valves

If the micro valves are grouped together in array structures, various control techniques can be used [12, 13, 14].

The control techniques can be classified in three categories [14]:

I. flow control based on the joining of a number of classical construction valves:

I.1. Pulse Number Modulation (PNM): in this case, the outputs of various identical micro valves are connected in parallel; the resulted flow will be proportional to the number of controlled valves;

I.2 Pulse Code Modulation (PCM): in this case, the micro valves connected in parallel have different flow sections, following a binary logic; the flow increment is much smaller than in the previous case;

II. flow control based on the modulation of the control signal of a sole digital valve:

II.1 PFM (Pulse Frequency Modulation): the method is less used due to the complexity of the control system;

II.2 PWM (Pulse Width Modulation): in this case, the frequency of the pulses remains constant, the flow being controlled through the variation of pulse duration.

III. mixed control techniques: a combination of the previous cases; for instance, a combination of PNM and PWM methods can be used in a control scheme that joins (n-1) valves of classical construction and a PWM controlled one.

6. Conclusions

The construction of the basic module is simple and does not require sophisticated manufacturing and mounting technologies. The proposed solution allows versatile configurations of micro valves in order to control different flow rate values in function of the application.

Actually the authors are concerned with the building of the experimental model of the basic module as well as with the development of relevant control strategies. The preliminary results are promising and recommend the further development of valve arrays that would integrate complex systems.

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