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Pressure Setting and Control System with PWM Direction Control Valve

PhD Prof. **Mihai AVRAM**[1], PhD Teach. Assist. **Victor CONSTANTIN**[2],
PhD Assoc. Prof. **Despina DUMINICĂ**[3], PhD Prof. **Constantin BUCŞAN**[4]

[1] University POLITEHNICA of Bucharest, mavram02@yahoo.com

[2] University POLITEHNICA of Bucharest, victor.f.constantin@gmail.com

[3] University POLITEHNICA of Bucharest, despina_duminica@yahoo.com

[4] University POLITEHNICA of Bucharest, constantin_bucsan@yahoo.com

Abstract: *The paper presents a system that sets and controls pressure in a given volume. The system features an original solution of PWM direction control valve. Intelligent control algorithms are implemented and comparatively tested in order to improve system performance.*

Keywords: *Pneumatics, pressure setting and control, PWM direction control valve, fuzzy logic, PI controller*

1. Introduction

The General Union Environment Action Programme to 2020 [1] states that more action is needed to protect nature and strengthen ecological resilience, boost resource-efficient, low-carbon growth, and reduce threats to human health and wellbeing linked to pollution, chemical substances, and the impacts of climate change. In line with this strategy, the Horizon 2020 Framework Programme for 2016-2017 [2] aims to prioritize the actions which take a systemic approach to promote a more resource efficient, greener and more competitive economy as a key part of smart, inclusive and sustainable growth.

Large scale promotion of pneumatic driving systems constitutes an efficient measure towards reaching these goals. An assessment of the field of pneumatic driving [3] leads to the identification of the main tendencies and perspectives, namely:

- strong development of pneumatics in the future; intensive fundamental and applied research that aims reducing the negative effects induced by the physical properties of the working fluid (such as reduced viscosity and high compressibility) is required;
- embedment of informatics in pneumatic driving systems and equipment, leading to the development of pneutronic systems;
- increase of reliability, functional accuracy and static and dynamic performance of actual pneumatic devices, as well as development and building of new types of high performance pneumatic equipment.

In this context, the paper presents an original conception pneutronic system aimed to set and control pressure in a given volume chamber using a PWM direction control valve developed by the authors. This type of equipment was chosen due to its speed, accuracy and relatively reduced price compared to other solutions with similar performances, features that recommend it for a large range of applications, from positioning systems to biomedical engineering [4 - 11].

2. Structure of the developed system

The system aims to set the pressure in a tank chamber of fixed volume V at a target value P_r and to maintain it constant. The functional scheme of the system is presented in Figure 1.

The structure of the system includes the following components:

- the tank Rz;
- pneumatic 3/3 direction control valves $M_1 \ldots M_{n+1}$; the valve M_n features a special construction developed by the authors
- pressure sensor T_P;
- microcontroller μC.

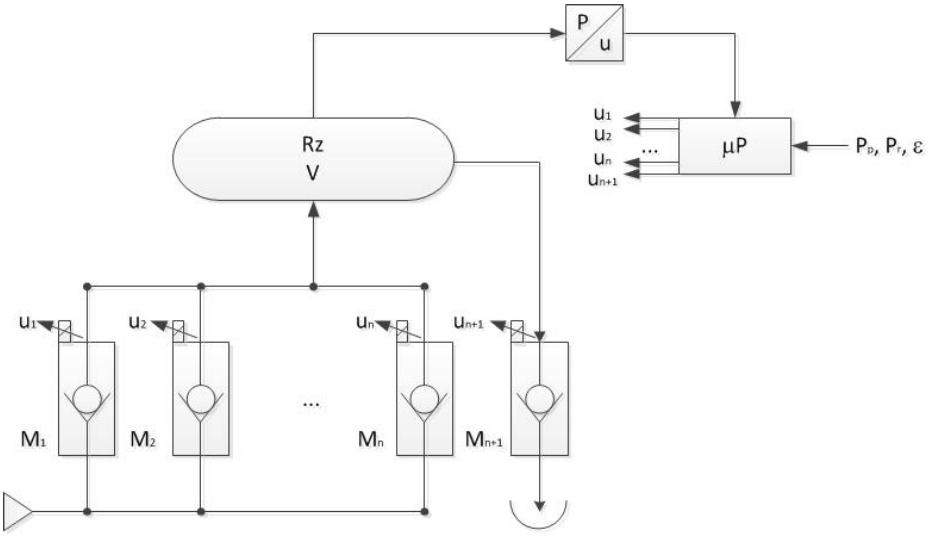


Fig. 1. Functional scheme of the system

The first (*n-1*) modules $M_1..M_{n-1}$are controlled using PNM (Pulse Number Modulation) technique: all the modules are controlled through control signals of the same constant value ($u_1 = u_2 = u_{n-1}$); in this case, the resulted flow will be proportional to the number of controlled valves. The flow delivered by the nth module M_n is controlled based on the modulation of the input signal of the digital valve using the PWM technique. The module M_{n+1} is used for draining or for generating a controlled flow loss $\Delta \dot{m} = f(u_{n+1})$.

Two stages are discerned during the functioning of the system if the initial pressure in the tank is assumed equal to the atmosphere pressure P_0:

- 1stStage: the direction control valves$M_1..M_{n-1}$are open (in the presence of the control signals$u_1 = u_2 = u_{n-1}$); the filling of the tank occurs through a flow section equal to the flow section $S_{n1} = (n-1) \cdot S_{nm}$, S_{nm} being the flow section of a module; the pressure in the tank will consequently rise; when it equals an imposed threshold pressure P_p the control signals$u_1 \ldots u_{n-1}$ stop and the valves$M_1..M_{n-1}$ are set on preferred position;
- 2nd stage: if threshold pressure P_p is reached, the valve $M_n$is supplied till the target value P_r is reached; this is the moment when the PWM control signal u_n stops.

Figure 2 presents the functional scheme of the special construction PWM direction control valve developed by the authors (the valve M_n from figure 1).

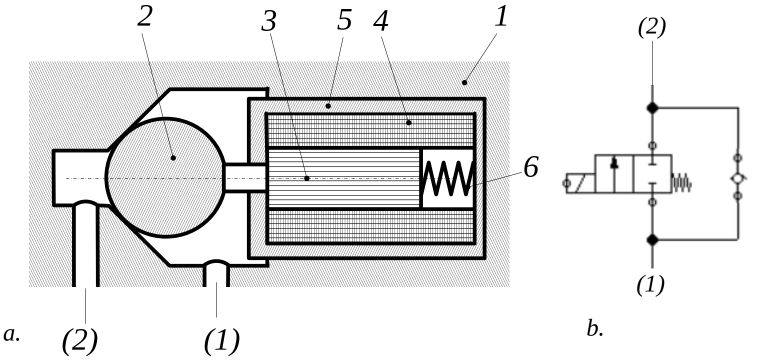


Fig. 2. Functional scheme of the PWM direction control valve. 1 – body; 2 – ball; 3 – mobile armature of the electromagnet; 4 – coil; 5 – fixed armature; 6 – spring; (1) – supply orifice; (2) – consumer orifice.

It is a small sized device (D_n = 2...3 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). An airflow is obtained this way through the consumer orifice (2), corresponding to the mean value of the real flow that passes through the internal circuit of the device.

The device does not achieve a continuous control of the instantaneous flow, but controls the mean flow in direct proportion to the duty cycle. 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.

Various control techniques can be used [12], based on the combining of different micro direction control valves of the same type grouped together in valve arrays, as well as on the controlling of the opening and closing times of the valve section.

3. Mathematical model of the pressure setting and control system

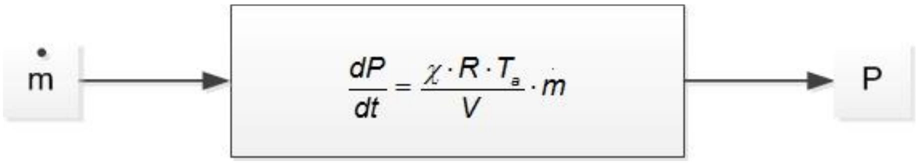
The notations used to describe the mathematical model are presented in Table 1.

TABLE 1: Notations used to describe the mathematical model

Notation	Meaning	Notation	Meaning
V	fixed volume of the tank chamber	S_{n1}	equivalent nominal section of the first *(n-1)* modules $M_1 \ldots M_{n-1}$
P_r	the target value of the pressure to be achieved in the chamber of fixed volume *V* (the set pressure)	S_{nm}	nominal section of a module
P	pressure in the chamber of fixed volume *V*	T_a	temperature in the chamber of fixed volume *V*
P_a	supply pressure	χ	adiabatic constant; χ = 1.4 [-]
P_p	threshold pressure; when is reached, the slide of the classical direction control valve *DC* moves back to the preferred position	$\dot{m}$	flow rate of the fluid that fills the chamber
P_0	atmosphere pressure	T	period of the pulses
R	universal gas constant; $R = 287.04\ [\mathrm{m^2/(s^2 \cdot K)}]$	t_a	pulse duration

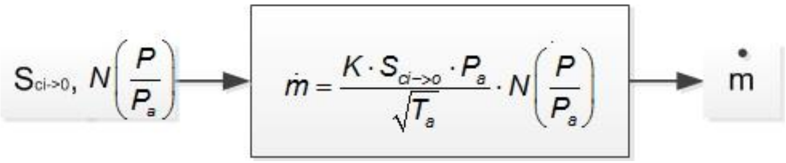
The mathematical model can be suggestively described using a block structure, as presented in continuation.

The variation of pressure in the chamber of fixed volume *V* can be written:



$$\frac{dP}{dt} = \frac{\chi \cdot R \cdot T_a}{V} \cdot \dot{m} \qquad (1)$$

where:



$$\dot{m} = \frac{K \cdot S_{ci\text{->}o} \cdot P_a}{\sqrt{T_a}} \cdot N\left(\frac{P}{P_a}\right) \qquad (2)$$

$$K = \sqrt{\frac{\chi}{R} \cdot \left(\frac{2}{\chi+1}\right)^{\frac{\chi+1}{\chi-1}}}\ ;\ K \cong 0.04042 s\sqrt{K}/m$$

$S_{ci->o}$denotes the flow section through the valve. In function of the functioning stage, it can be described as following:

$$\text{P, S}_{cm} \longrightarrow \boxed{S_{ci->o} = \begin{cases} S_{n1} & \text{if} \quad P_0 \le P \le P_p \\ S_{cm} & \text{if} \quad P_p \le P < P_r \end{cases}} \longrightarrow \text{S}_{ci->0} \tag{3}$$

The flow sectionS_{cm} through the PWM controlled direction control valve can be written:

$$t \longrightarrow \boxed{S_{cm} = \begin{cases} S_{nm} & \text{if} \quad rem(\frac{t-t_p}{T}) \le t_a \\ 0 & else. \end{cases}} \longrightarrow \text{S}_{cm} \tag{4}$$

The function *rem* denotes the remainder of the division between the two values; t_p denotes the moment of time when the pressure P_p is reached (and the PWM controlled valve is actuated).
$N\left(\frac{P}{P_a}\right)$ denotes the flow rate number.

The flow rate number $N\left(\frac{P}{P_a}\right)$is defined as following:

$$P \longrightarrow \boxed{N\left(\frac{P}{P_a}\right) = \begin{cases} 1 & if \quad 0 < \frac{P}{P_a} \le 0.528 \\ \text{a} \cdot \left[\left(\frac{P}{P_a}\right)^{2/\chi} - \left(\frac{P}{P_a}\right)^{(\chi+1)/\chi}\right]^{1/2} & if \quad 0.528 < \frac{P}{P_a} \le 1 \end{cases}} \longrightarrow N\left(\frac{P}{P_a}\right) \tag{5}$$

$$a = \sqrt{\frac{2}{\chi-1} \cdot \left(\frac{\chi+1}{2}\right)^{\frac{\chi+1}{\chi}}}\ ; \ a = 2.6143[-].$$

The mathematical model based on these relations is depicted in Figure 3.

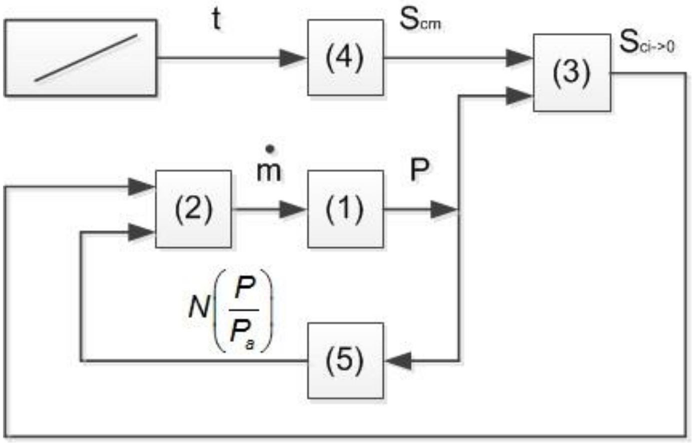


Fig. 3. The block structure that describes the mathematical model of the system.

The analysis of the functioning of the automated system for pressure setting and control can be performed analytically as well as numerically [13].

4. The control algorithm

A series of control algorithms were tested in order to improve system performance:
- the use of a constant duty cyclet_a/T=50% (classical work algorithm);
- dynamic variation of the pulse duration t_a using fuzzy logic;
- implementation of a PID controller.

The three cases were numerically simulated using SIMULINK. The two controllers (fuzzy and PID) were implemented with the help of predefined blocks chosen from the software libraries. The choice of the method that allowed the filling of the tank in the shorter time and with the smallest error constituted the purpose of the simulation.

Three triangular sets of inputs, respectively outputs, directly connected, were used in the case of the fuzzy controller. The physical setting of the input and output values was possible also due to the existence of an experimental set-up in an incipient phase.

The ideal control law was used in the case of the PID controller [14]:

$$u(t) = K_R \cdot \varepsilon(t) + K_I \cdot \int \varepsilon(t)dt + T_d \cdot \frac{d\varepsilon}{dt} \qquad (6)$$

Figure 4 presents the results of the simulations, obtained for a target pressure P_r=3bar, using a threshold pressure P_p=2bar. The frequency of the PWM signal was fixed at a value of 10Hz in all three cases in order to be able to compare results.

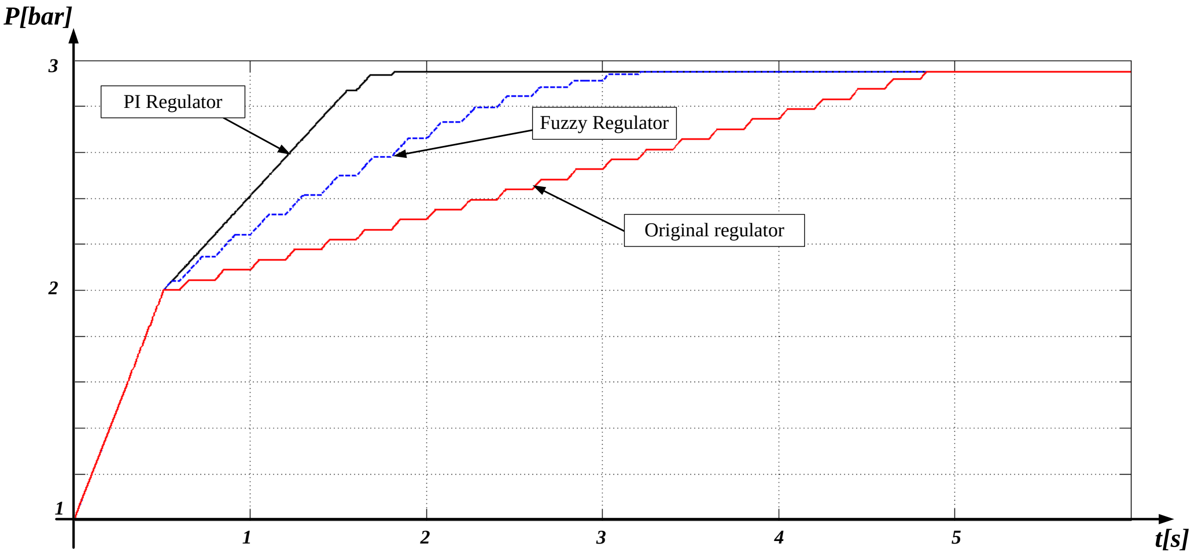


Fig. 4. Comparison between the performances of the three control algorithms

It can be noticed that the classical work algorithm (which implies a fixed duty cycle of t_a/T=50%) leads to the filling of the tank in the range [P_p...P_r] in a time that is twice the time required when the fuzzy algorithm is used. In the case of the latest, a decrease of the pulse duration was noticed in the proximity of the target pressure. The target pressure can be more rapidly reached in the case of the classical algorithm if the duty cycle is increased, but the error will also increase.

In the case of PID control, proportional, integrative and derivative gains were chosen according to Ziegler-Nichols method. It implies the initial setting of all values to 0, followed by the increase of the proportional component till obtaining constant oscillations of the system. The absence of overshoot, as well as of a physical way of compensating its occurrence led to the removal of the derivative gain, finally resulting a PI controller.

According to simulation results, the use of the PI algorithm leads to the rapid filling of the tank till an intermediary pressure$P_{int}>P_p$, behaviour corresponding to a duty cycle of 100%. The decrease of the duty cycle as result of the controller intervention can be noticed in the range [$P_{int}\ldots P_r$].

5. Testing and validation of simulation results

A test set-up was developed in order to validate the simulation results. It includes an electronic control unit based on an Atmel microcontroller, as well as the electronics needed in order to amplify the control signals from the TTL level to the level required for driving the valve electromagnets (24V/0.3A, respectively 7V/2A). Signals were amplified using MOSFET (IRF510) and BJT(BD139) transistors, according to system requirements. Voltage regulators (LM78XX, respectiv LM338) were also used due to the various levels of stabilised voltage needed in the system (5V, 7V, 12V si 24V) in order to obtain an unified supply of the electronic unit. The system works in closed loop, the current pressure at the valve level being read by an analog voltage output pressure sensor. The principle scheme of the set-up is presented in Figure 5.

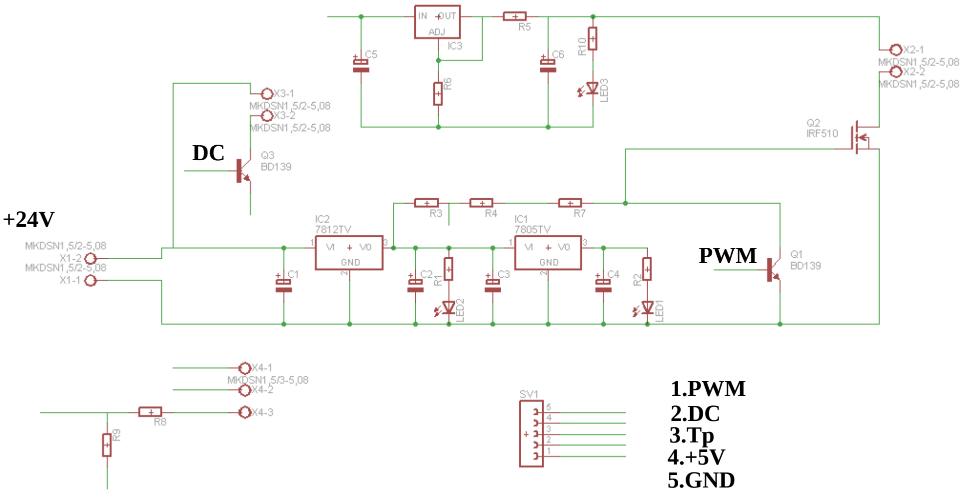


Fig. 5. The electronic scheme of the control unit

The Atmega328 microcontroller is programmed in the C language and contains the code needed for the control of the pressure setting system, including the control algorithms. The system contains also a FTDI interface that allows the collection and storage of data regarding the system performance on a PC for further processing and interpretation.
The experimental research validated the simulation results.

6. Conclusions

The research proves that the proposed system allows the setting of a target pressure in a tank with an imposed error. The system is easy to configure, being mostly composed of standard equipment. An important functional role is played by the original conception PWM direction control valve. The construction of the device is simple and does not require sophisticated manufacturing and mounting technologies. The implementation of intelligent control algorithms increases the system performance, the best results being obtained when a PI controller is used.

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