EXPERIMENTAL ANALYSIS OF THE PNEUMATIC DISTRIBUTOR WITH MOBILE TRANSLATION ARMATURE AND DIGITAL PWM CONTROL

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The paper presents the experimental analysis of a distributor made - in its conception - by the group of authors in terms of static and dynamic characteristics. The results show that the designed distributor can be used in similar applications that use company distributors, for example, to control pneumatic actuators with multiple positioning. The performed experiments demonstrated the concordance with the theoretical developments in the reference works in the field and the similarity with the characteristics of some company products.

Keywords: pneumatic distributor, PWM control, average flow (mediated).

1. Introduction

Proportional pneumatic distributors controlled by modulated pulses have gradually replaced analog ones, especially after the company's achievements have reached remarkable reliability indicators. The increase in the performances of the digital proportional distributors is closely related to the constructive solution adopted and the materials used in the realization of the components (subassemblies).

The most frequently used variant in the realization of these distributors involves an electromagnet with the longitudinal translation of the movable core, the latter driving the pneumatic valve on / off for the pneumatic path [1], [2]. In such a configuration, a series of aspects are highlighted, which contribute to the increase of static and dynamic performances, related to:

- the shape and material of the mobile magnetic core to obtain a residual induction of negligible values;

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- the shape of the shut-off valve of the compressed air (gas) flow, of the seat on which it works, as well as the nature of the materials from which the two components are made (seat + valve);
- the nominal travel stroke that the valve must perform to guarantee the flow of air through the distributor body, according to the average nominal data (named, usually given in [l/min]);
- the shape and dimensions of the electromagnet to achieve the closure of the magnetic field lines by ferromagnetic material (maximum solemnity), with a shortening time as short as possible;
- the nominal supply voltage and the current absorbed by the coil in the active state, which leads to the corresponding dimensioning of the electromagnet (the number of turns and the diameter of the copper wire used to make the winding);
- the shape and material of the spring in order to ensure that the valve is brought back to its original position in a minimum of time;
- the clearance between the movable core and the electromagnet housing results in a coefficient of friction as small as possible.

In addition, several additional factors must be taken into account when choosing a proportional distributor taking into account:

• working environment: air, oxygen, nitrogen, steam, etc., as well as the operating temperature of the environment;
• the nominal flow and constants specific to the working environment, including the necessary filtering required by the operation in the respective environment;
• inlet pressure, outlet pressure variation, pressure drop on the distributor;
• characteristics of the actual operating environment (temperature, explosion resistance, sealing);
• supply voltage: 24 Vdc, 12 Vdc. etc., as well as the maximum power required;
• losses on the operating line: pressure maintained, pressure released;
• other aspects related to operation: vacuum control, unique construction.

This paper presents a version of a pulse-controlled distributor of its design, which can be used in applications of medium complexity, similar to the achievements of the company [3], [10].

2. Proportional pneumatic distributor controlled in pulse with mobile reinforcement with translation movement

In the experiments, a pneumatic distributor controlled by PWM (Pulse Width Modulation) was used, with mobile translational reinforcement, in which the constructive elements are mainly presented in Fig. 1.

The basic idea of the distributor was to close the magnetic field lines with ferromagnetic material characterized by a relative magnetic permeability $\mu_r \gg \mu_{air}$. If this principle is maintained, then the electromagnetic force developed will be large enough to attract the mobile armature to the fixed magnetic core, which can be realized with a high frequency.

Fig. 1 shows the two stable operating positions, namely:

• Fig. 1 CLOSED corresponds to the preferential situation; in this case, the electromagnet is not powered, and the movable magnetic core, which actually materializes the flat valve of the equipment, is in contact with the cylindrical seat processed in the left conical part under the action of the force developed by the helical spring; in this case, the flow section through the equipment is zero;

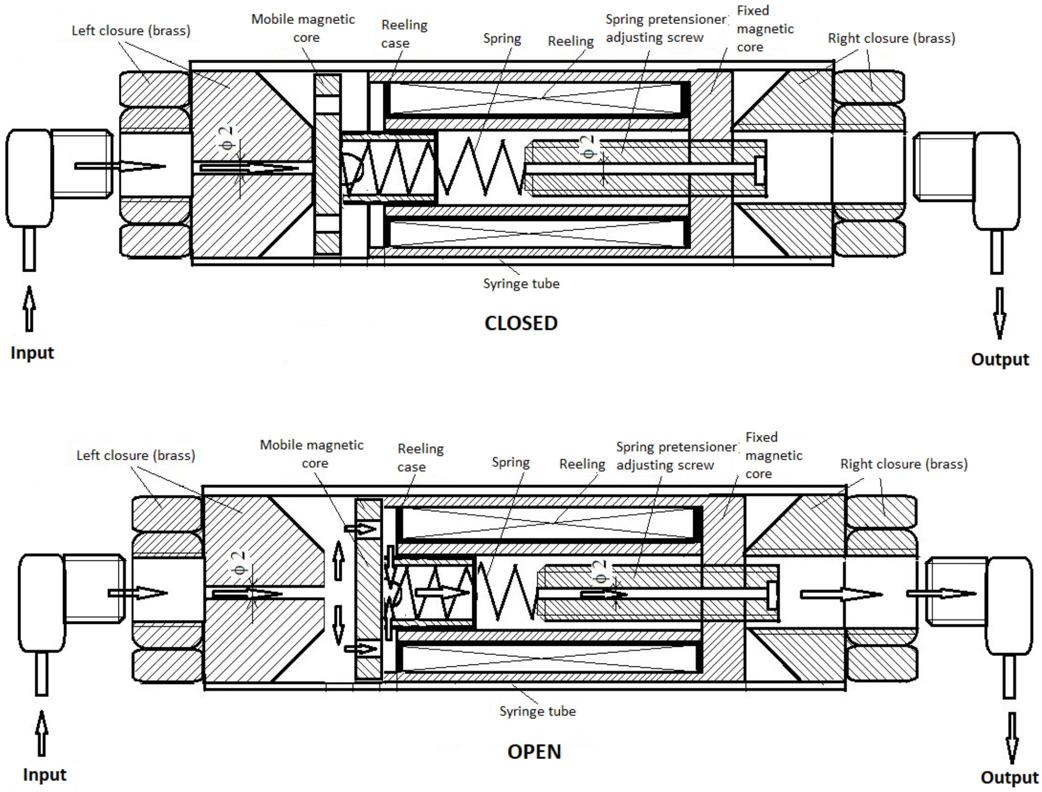


Fig.1. Proportional pneumatic distributor assembled according to cases CLOSED and OPEN respectively.

• Fig. 1 OPEN corresponds to the second position, when the electromagnet is supplied with voltage; in this case, the moving magnetic core moves to the right under the effect of the electromagnetic force; in this case, the flow section through the distributor has the nominal value, and at the outlet of the distributor the airflow will be the nominal one.

The dimensions of the dispenser have been calculated so that its components can be assembled into an average syringe body. In this way, in addition to the formal aspect related to obtaining a stable configuration, it is possible to effectively measure the movement of the mobile armature with an optical sensor; also, by using the screw spring pre tensioning adjustment, it is possible to change the resistant force of the spring, aspect imposed by the on / off dynamics of the distributor.

The flow port was considered 2 mm (diameter), as the comparison of static and dynamic characteristics with firm achievements was followed [10]. Also, the value of 24 V dc was taken as the working voltage for the active case and used by PWM-controlled pneumatic dispenser companies (in fact, the 24 V dc voltage is the typical value found in all applications with programmable controllers associated with distributors). An assembled image of the distributor can be seen in Fig. 2; all functional elements are sized so that they can be assembled into a 10 ml syringe body.

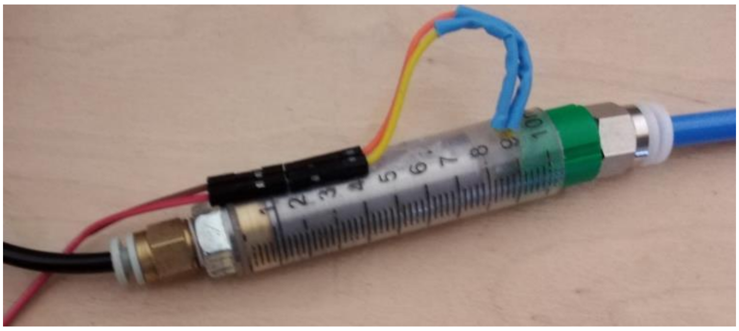


Fig.2. Pneumatic dispenser assembled in a syringe body.

The detailed design of the 2/2 distributor and the way to include the components in the "improvised" housing are presented in the paper [1].

3. Scheme and equipment used in the experimental study of the pneumatic distributor

Fig. 3 shows how to perform the experiments for the distributor study presented in Chapter 2. Thus, an executable accomplished in LabVIEW 2011 is used, and the interface with the distributor is provided by the NI USB 6001 module and the electronic amplitude and power control circuit, which guarantees galvanic separation between module and distributor [1]. The D_{IM} distributor receives the P_{int} pressure at the inlet, and its output is connected to a constant volume tank V, which is followed by the TP pressure and flow transducers TD, the end being the manual flow regulator DrP in the atmosphere. Using the scheme in Fig. 3, the experiments set out in Chapter 4 were carried out. It should be noted that a pressure reducer with a maximum outlet of P_{intmax} = 4 bar was provided for the experiments.

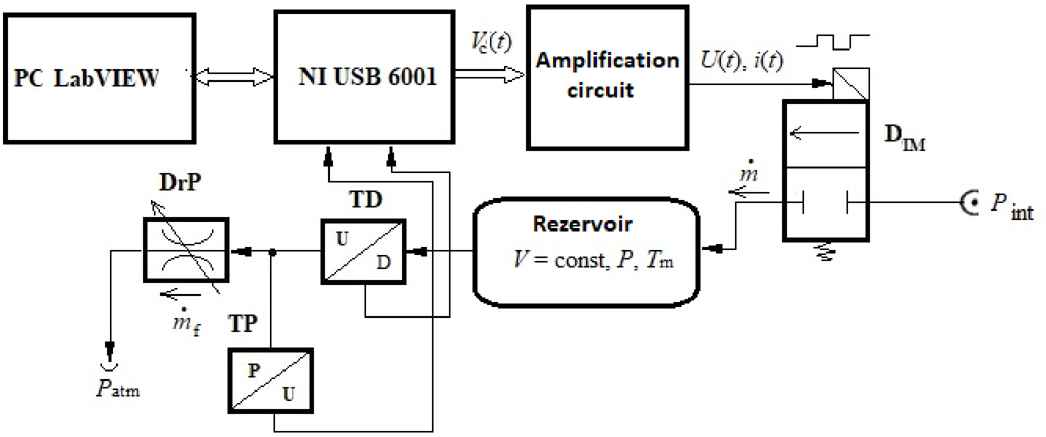


Fig.3. Block diagram of the assembly used in experiments.

4. Experimental analysis of the proposed distributor

All the experiments performed on the distributors used in the paper had as starting point the principle scheme from Fig. 3.

The following experiments were performed for the designed distributor:

4.1. Behavior of restricted frequency distributor; for 10 frequency values - 5 Hz, 10 Hz, 15 Hz, 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz, 45 Hz, 50Hz - with a filling factor (in each experiment) of 30%, 50 %, 70%, the average volumetric flow was measured, using the local indication of the flow meter, respectively the averaged by the digital oscilloscope, with a constant atmospheric outlet pressure of 1 bar, at a supply pressure of 4 bar. The results obtained are presented in table 1.

Table 1

Static average flow characteristic - PWM frequency function (restricted)

P_{int} = 4 bar; $P_{exhaust}$ = 1 bar

Filling factor FU [%]	Freq. [Hz]	5	10	15	20	25	30	35	40	45	50	Abs. error [l/min]	Rel. error [%]	Mean value
FU = 30%	Flow-meter [l/min]	13.6	14.1	13.2	15.4	15.3	13.1	13.1	12.5	13.2	12.5	1.83	13.52	13.6
	Osc. [V]	1.86	1.73	1.71	1.74	1.74	1.59	1.49	1.48	1.61	1.63	0.193	11.72	1.658
	[V] conv. into [l/min]	15.2	14.19	14.0	14.27	14.27	13.04	12.22	12.14	13.21	13.37	1.578	11.71	13.6

FU = 50%	Flow-meter [l/min]	16.1	16.3	16.1	17.2	16.8	15.4	16.1	16.1	15.1	15.4	0.98	6.184	16.06
	Osc. [V]	2.01	1.83	1.81	1.87	1.88	1.87	1.75	1.82	1.86	1.84	0.145	7.875	1.854
	[V] conv. into [l/min]	17.4	15.85	15.7	16.19	16.29	16.19	15.16	15.77	16.11	15.94	1.26	7.875	16.06
FU = 70%	Flow-meter [l/min]	17.1	17.1	18.2	19.1	19.1	19.1	18.3	18.2	18.6	0.1	0.64	3.428	16.49
	Osc. [V]	2.16	2.16	2.01	1.98	0.01	2.03	1.96	2.02	2.04	2.02	0.11	5.45	1.839
	[V] conv. into [l/min]	19.3	19.37	18.0	17.75	0.089	18.20	17.57	18.11	18.29	18.11	1.01	5.444	16.49

The experimentally high values presented in table 1 have a high degree of inaccuracy due to the equipment they were made. It should be noted that the Festo flow meter used has - in the working range 5 ... 50 l/min - an error of 5%, which leads to an indication of ± 2.5 l/min deviation from the actual value; in fact, if the values in the table are inspected, it is observed that there are no deviations between them greater than 2.5 l/min at the same filling factor.

Because with the digital oscilloscope, the analog signal was taken from the output of the flow meter, the measurement errors propagate, that is why there are situations highlighted in the table with absolute/relative deviations superior to those obtained with the flow meter. From the analysis of the experimental data, it is concluded that the distributor operates normally in relation to the range of frequencies for which the experiments were performed, and the behavior in relation to the filling factor brings confirmation of the previous idea. Moreover, if a ratio is made between the average values (last column in table 1), the non-linear character of the distributor in relation to the filling factor is observed (the ratio between the average values at 50% compared to 30% is equal to 1.187685, compared to the value 1.147408 obtained as a ratio between the mean at the filling factor 70% and the mean at 50%).

4.2. Behavior of the distributor in frequency without restriction; for 10 frequency values - 5 Hz, 10 Hz, 15 Hz, 20 Hz, 25 Hz, 30 Hz, 35 Hz, 40 Hz, 45 Hz, 50Hz - with a fill factor (in each experiment) of 30%, 50 %, 70%, the average volumetric flow was measured, using the local indication of the flow meter, respectively the mediation performed by the digital oscilloscope, with the exhaust pressure in the atmosphere without any restriction, at a supply pressure of 4 bar. The results obtained are presented in table 2.

Table 2

Static average flow characteristic - PWM frequency function (unrestricted)

P_{int} = 4 bar $P_{exhaust}$ = 1 bar

Filling factor FU [%]	Freq. [Hz]	5	10	15	20	25	30	35	40	45	50	Abs. error [l/min]	Rel. error [%]	Mean value
FU = 30%	Flow-meter [l/min]	11.1	10.01	10.21	10.02	10.01	10.1	10.1	10.01	10.9	10.1	0.77	7.63	10.26
	Osc. [V]	1.15	1.23	1.41	1.35	1.36	1.355	1.361	1.273	1.422	1.461	0.125	9.45	1.337
	[V] conv. into [l/min]	8.820	9.434	10.81	10.35	10.43	10.39	10.44	9.764	10.91	11.21	0.9652	9.45	10.26
FU = 50%	Flow-meter [l/min]	11.2	12.7	13.1	13.3	13.2	13.1	13.4	13.1	15.1	14.1	-1.86	14.2	13.23
	Osc. [V]	1.61	1.64	1.71	1.72	1.68	1.66	1.66	1.52	1.76	1.83	-0.165	9.95	1.679
	[V] conv. into [l/min]	12.69	12.92	13.47	13.55	13.24	13.08	13.08	11.98	13.87	14.42	-1.33	9.95	13.23
FU = 70%	Flow-meter [l/min]	17.1	16.5	17.2	16.4	16.5	17.1	17.1	16.2	18.1	18.1	1.07	6.38	17.03
	Osc. [V]	1.96	1.94	1.96	1.97	1.98	1.95	1.98	1.98	2.11	2.14	0.151	7.66	1.997
	[V] conv. into [l/min]	16.71	16.54	16.71	16.80	16.89	16.63	16.89	16.89	17.99	18.25	1.2961	7.66	17.03

Compared to the data obtained with restricted output (table 1), in the case of experimental data obtained in the unrestricted situation, there is a reduction of absolute and relative error, respectively, which a subsonic regime can explain for all frequencies all fillers used in the experiment.

In addition to the reduction of measurement errors, if the procedure is the same as in the previous case and a ratio is made between the average values (last column in Table 2), there is a reduction in the nonlinearity of the distributor concerning the filling factor. % compared to 30% equal to 1.289628, compared to the value of 1.283763 obtained as a ratio between the average at the filling factor 70% and the average at 50%).

4.3. Distributor behavior at variable filling factor*;* the experimental study for this situation was done at the variation of the filling factor FU [%] between 10% and

90% with a step of 10%, at a supply pressure P_{int} = 4 bar, without restriction on output. The results of the experiments - at the control signal frequencies of 5 Hz, 25 Hz, and 50 Hz - are presented in table 3.

Table 3

Static average flow characteristic - depending on the filling factor FU [%]

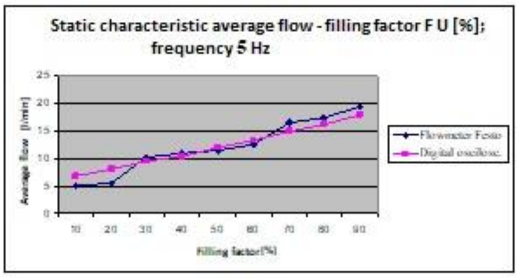
P_{int} = 4 bari; $P_{exhaust}$ = unrestricted

		Mean flow [l/min]									
Freq. [Hz]	Filling factor FU [%]	10	20	30	40	50	60	70	80	90	Mean value
5 Hz	Flow-meter [l/min]	5.01	5.51	10.32	11.02	11.51	12.62	16.51	17.52	19.48	10.95
	Osc. [V]	0.865	1.043	1.214	1.323	1.513	1.612	1.904	2.054	2.266	1.3794
	[V] conv. into [l/min]	6.8666	8.280	9.637	10.502	12.010	12.796	15.114	16.305	17.9880	10.95
25 Hz	Flow-meter [l/min]	6.52	8.01	9.81	10.31	14.42	15.51	17.42	18.42	20.51	12.093
	Osc. [V]	1.02	1.15	1.39	1.51	1.78	1.82	2.01	2.17	2.26	1.511
	[V] conv. into [l/min]	8.1634	9.204	11.125	12.085	14.246	14.566	16.087	17.367	18.0875	12.093
50 Hz	Flow-meter [l/min]	6.92	7.51	10.62	12.02	14.12	16.01	18.21	19.22	21.52	12.615
	Osc. [V]	1.1	1.22	1.51	1.61	1.73	1.92	2.02	2.22	2.31	1.564
	[V] conv. into [l/min]	8.8724	9.840	12.179	12.986	13.954	15.486	16.293	17.906	18.6321	12.615

For a comparative analysis of the obtained results, Fig. 4 is presented the three situations graphically (at the three frequencies), determinations obtained with the Festo flow meter respectively the digital oscilloscope.

The analysis of the graphical representations in Fig. 4 shows the approximately linear character of the characteristics, with the observation that the determinations made with the digital oscilloscope have better linearity (according to expectations) than those indicated by the Festo flow meter.

However, with the increasing frequency of control pulses, the nonlinear character is more prominent, especially from the analysis of the representations in Fig. 4, c. At the same time, from the analysis of the average values for the three frequencies, a slight increase with the increase of the frequency is observed, which is to the distributor's operation (the averaging of the instantaneous flow values is better at higher frequencies). Consequently, we can say that the designed distributor is by the desired parameters by theoretical calculations [1].



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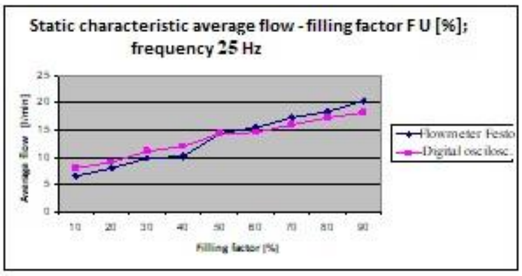

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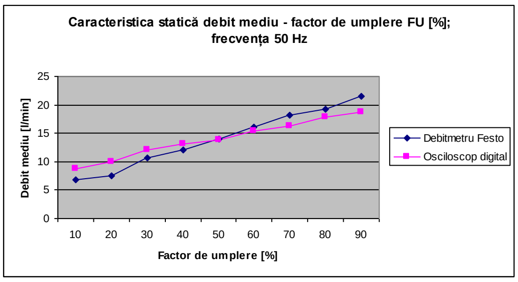

c)

Fig.4. Static average flow characteristic - depending on the duty cicle FU [%]; a) 5 Hz control frequency case; b) 25 Hz control frequency case; c) the case of the control frequency 50 Hz.

4.4. Behavior of the distributor at variable filling factor, inlet pressure 2 ... 4 bar*, restriction of 1 bar at the outlet;* this experiment was performed at inlet pressures P_{int} = 2 bar, 3 bar, 4 bar, at each set value being built an operating cycle depending on the filling factor - between 10% and 90%, with a step of 10% - at which the inlet pressure remained constant, at each value of the filling factor being achieved, from the pneumatic throttle, a constant exhaust pressure in the atmosphere of 1 bar. The results are presented in table 4, with the graphical representation in Fig. 5.

Table 4

Flow determinations at constant outlet pressure and supply pressures 2, 3, 4 bar, PWM frequency 25 Hz

	PWM pulse width									Notes
Nr.crt.	10%	20%	30%	40%	50%	60%	70%	80%	90%	Filling factor
Exhaust Pressure [bar]	1 bar									Display pressure transducer
Flow 2 bar [l/min]	0	0	0.2	0.4	1.5	2.3	3.3	3.7	7.6	Average values shown on flowmeter numeric display
Flow 3 bar [l/min]	0.05	0.1	0.8	3.4	6.5	10.3	12	14.5	16.2	
Flow 4 bar [l/min]	0.5	1.8	4.7	8.3	11.3	13.5	16.4	18.2	20	

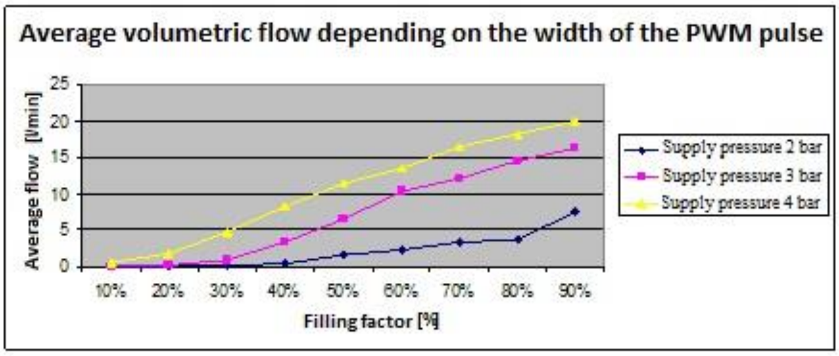

Fig.5. Representation of the volumetric flow mediated according to the supply pressure and filling factor

The results obtained are consistent with previous experiments; they show an increase in average flow with increasing inlet pressure. If we take into account the pressure restriction (1 bar) and refer to the average flow rate between 2 bar and 4 bar, it is observed that in the last column (for 90% FU), the value at 4 bar (relative to ¾) is approximately double-sided of value at 2 bar. It is concluded that the distributor is entirely open to both pressures under investigation.

Also, from the representations from 3 bar and 4 bar, the plot dependence's nonlinear character is observed by the theoretical analysis and the simulated representation obtained with the AMESim environment [1].

5. Specifications regarding the equipment used in the experiments

As mentioned above, the scheme in Fig. 3 allows the experimental determination of the instantaneous and mediated characteristics of the analyzed distributor. Some clarification is needed on the equipment used in signal generation and measurement of characteristic indicators.

Due to the aspects highlighted above, it was preferred, where possible, to use the digital oscilloscope. Thus, the LabVIEW 2011 programming environment was used to generate the signals, and the connection to the test board was made via the NI USB 6001 module. In frequency and amplitude. Oscilloscope catalog data specify operation up to 70 MHz with a measurement error below ± 3%, so a relatively "modest" measurement accuracy. Also, the NI USB 6001 module has a high resolution (14-bit analog-to-digital conversion), but for low-frequency signals, it allows the acquisition on a channel up to 10 k-samples, i.e., it is not recommended to operate when acquiring fast signals variables, theoretically, over 100 Hz, practically well below this limit when using several input-output menus working in parallel).

An instantaneous volume tank with a flow distributor and transducer has been provided to "quiet" the instantaneous flow signals. The tank's volume - about

1.5 liters - is small; however, the literature presents schemes with two tanks, each of 5 liters in volume, one specially used for temperature measurement [3].

Pint inlet pressure is set to the desired value by the pressure regulator - type GR 200-08L - which allows a continuous adjustment between 0 bar and 4 bar, with an accuracy of 2.5%. The TP pressure transducer, mounted downstream of the distributor, is from IFIM, code PG2455, in IO-Link configuration, has a local indicator with three decimals, in the range 0 or 4 bar analog signal in the range 4 ... 20 mA. Unfortunately, it is not intended for dynamic measurements; however, the catalog data specify analog signal dynamics up to 75 Hz.

TP flow transducer - model SFE3-F500-L-W18-2PB-K1, manufactured by Festo - allows volumetric flow measurements, expressed in [l/min], in 5… 50 (local indication with 3 decimal places), respectively DC voltage signal in the range 1V… 5V. The measuring accuracy is ± 5%, so a very fair value, so that a measured indication must be seen in a range [I_i - 2.5 l/min; I_i + 2.5 l/min]. It has a response time of 50 ms, making it usable for dynamic signals with a frequency of up to 10 Hz (theoretically 20 Hz).

The pneumatic drill DrP allows a manual adjustment of the purge section in the atmosphere; with the help, it is possible to manually set a certain exhaust pressure in experiments.

With the help of this equipment, all the determinations set out in chapter 4 of this paper have been carried out, and the results obtained must be considered.

5. Conclusions

We will comment on the experimental results presented concerning the theoretical assumptions obtained by simulation. These comments refer to the digital dispenser designed and built into the syringe body.

The works [1], [2], [4 ... 7] theoretically analyze the models of the pneumatically controlled pneumatic distributor, as well as a series of results obtained by simulation (for example, in [1], the simulation of the distributor in the environments is done AMESim and Simulink and compare the results obtained with those of this paper). Due to the limitations of the editorial space, we must present the results obtained partially.

The behavior in the dynamic regime at the triggering/triggering of the electromagnetic relay was presented in detail in paper [4], and by simulating AMESim and Simulink [1], they proved to be consistent with physical reality. The stationary behavior, described by the experiments presented in this paper (Chapter 4), highlights the distributor's operation designed similar to a company achievement [10].

The representations in Figs. 4 and 5 are similar to those presented for the company products [10], and the similarity - in appearance - with those determined by simulation with the AMESim method [1] shows the viability of the designed distributor.

At the same time, the analysis of the experimental data shows more obviously the concordance with the representation - obtained by simulation - of the dependence of the average flow on the ratio of the inlet/outlet pressures.

The data obtained and the experimental surveys performed for the distributor designed for various experimental cases confirm - without exception - the theoretical concepts and the results obtained by simulation. The experiments presented and the results obtained may represent the premises for developing digital pneumatic equipment capable of working in high-performance applications.

R E F E R E N C E S

[1]. *I.A.Sgârciu*, Contribuții la analiza, realizarea și utilizarea distribuitoarelor pneumatice proporționale comandate în impulsuri (Contributions to the analysis, realization and use of pulse-controlled proportional pneumatic distributors), PhD Thesis, University Politehnica of Bucharest, 2021.

[2]. *M.Avram, C.Bucșan* – Sisteme pneumatice inteligente (Intelligent pneumatic systems), Ed.Politehnica Press, 2014, ISBN: 978-606-515-557-2.

[3]. *A.Messina, N.I.Giannoccaro, A.Gentile* - Experimenting and modelling the dynamics of pneumatic actuators controlled by the pulse width modulation (PWM) technique. Mechatronics 2005;15(7):859–881.

[4]. *I.A.Sgârciu, A.A.Năstase, A.Nedelcu, B.Nedelcu, V.Sgârciu,* Theoretical and experimental research on digital pneumatic on / off distributors, CSCS 23, pp. 62 – 67, May 2021, Article number 948106223, ISBN: 978-166543939-8, DOI: 10.1109/CSCS52396.2021.00018.

[5] *M Avram, A I Sgârciu and C Bucşan* - Trends and perspectives in proportional pneumatics, *IOP Conf. Ser.: Mater. Sci. Eng.* 997 012034, ISSN: 17578981, DOI: 10.1088/1757-899X/997/1/012034.

[6] *M. Avram, V. Constantin, D. Duminică, C. Bucșan* - Pressure setting and control system with PWM direction control valve, HIDRAULICA (No. 3/2016), Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics, ISSN 1453 – 7303.

[7] *M. Avram, C.Bucsan, L.A.Cartal, D.Duminică,* PWM Controlled Proportional Equipment, Applied Mechanics and Materials Vol. 245, pp. 107-112, ISSN 1662-7482, 2013.

[8] *A.A.Năstase, I.A.Sgârciu, A.Nedelcu, B.Nedelcu, V.Sgârciu* - Alternative Solutions for Making Impulse Ordered Proportional Valves, ECAI-2021, ISBN: 978-166542534-6, DOI: 10.1109/ECAI52376.2021.9515177.

[9] *L. Mihai, S.M.Zapciu* –A testing model for the mechatronic system, Scientific Bulletin, serie D, vol.83, nr.1, 2021, pp.113-127, ISSN: 1454-2358.

[10] *** MATRIX Catalog, 2018.

[11] *M.Taghizadeh, A.Ghaffari, F.Najafi* - Modeling and identification of a solenoid valve for PWM control applications, C. R. Mecanique no. 337, pages 131–140, 2009.