Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

THE DESIGN OF A THREE WAY PNEUMATIC VALVE

Terenziano RAPARELLI*, Pierluigi BEOMONTE ZOBEL**, Francesco DURANTE** and Gianpaolo GAGNOLATO

* Dipartimento di Meccanica, Politecnico di Torino
Corso Duca degli Abruzzi 24, Torino, Italy
terenziano.raparelli@polito.it
** DIMEG, Università di L'Aquila
67040 Roio Poggio, L'Aquila, Italy

ABSTRACT

The paper presents the design and the construction of the power part of a three-way pneumatic valve that uses a pilot stage developed by Belforte et al., based on a compact turbulent amplifier that uses the laminar-turbulent transition of fluidic jets. The valve can be used to drive a power stage of pneumatic circuits. It has a low energy consumption to switch. The pilot stage uses an acoustic signal generated by a piezoelectric device to brake the laminar flow. The power part of the valve has been designed to obtain an high conductance and a good dynamic performance. The design of the power valve, by a mathematical model using concentrated parameters, is presented. The prototype was constructed and tested. The results of the experimental test are also reported and discussed.

KEY WORDS

Pneumatics, valve design

NOMENCLATURE

p_0 :	*recovered pressure*
p_s :	*supply pressure*
p_c :	*control pressure*
C_i :	*conductance*
R_i :	*resistance*
G_i :	*flow-rate*
D_1 :	*control diaphragm*
D_2 :	*power diaphragm*
V :	*voltage*
Q_N:	*normal flow-rate*

INTRODUCTION

The paper presents the design and the construction of a three-way pneumatic valve that uses a pilot stage developed by Belforte et al. [1,2], based on a compact turbulent amplifier that uses the laminar-turbulent transition of fluidic jets. The valve can be used to drive a power stage of pneumatic circuits. It has a low energy consumption to switch. The pilot stage uses an acoustic signal generated by a piezoelectric device to brake the laminar flow. The supply pressures at the pilot stage is about 2000 Pa, the maximum pressure recovered at the receiving nozzle is about 1200 Pa. The supply pressure at the power section is fixed at 3 bar. The power part of the valve has been designed to obtain an high conductance and a good dynamic performance. The operating principle of the low pressure/high pressure interface is based on a flapper nozzle sensor. The classical architecture of the flapper nozzle in a valve is formed by a circular hole, where supply air comes, that faces to the flapper [3]. The idea was to use an annular shape of the hole that supplies air and a circular shape inside it bonded to the exterior. In this way the air flux flows to the exterior by two surfaces and it is possible to reduce the displacement of the flapper. The design of the power valve is also presented. The prototype was constructed and tested. Finally the results of the experimental test are reported and discussed.

THE PILOT STAGE

The pilot stage of the valve was developed and constructed by Belforte et al. [1,2]. It is based on a compact turbulent amplifier and it uses the laminar-turbulent transition of fluidic jets. Between the emitting and the receiving nozzles there is a diffuser, to improve the amplifier performance, and an open chamber. The open chamber is open to the environment and the control signal is located in it.

The control signal is obtained by an acoustic signal generated by a commercial low power piezoelectric element (power supply = 1 V, max frequency = 17100 Hz, max acoustic amplitude = 94.5 dB). It emits a sound disturbance capable of producing jet transition. In fact the fluidic jet shows a high sensitivity to acoustic signal whose frequency is close to the natural frequencies of the jet. Some experimental tests were carried out on the pilot stage to define the optimal values of the supply pressure, voltage and frequency of the piezoelectric element. The distance between the jet and the piezoelectric element is 1.2 mm to minimize the energy consumption.

The characteristic geometrical dimensions of rectangular nozzles are as follows.

Emitting nozzle-Receiving nozzle distance = 14 mm
Emitting nozzle section = 0.5 mm x 0.4 mm
Receiving nozzle section = 0.5 mm x 0.4 mm
Diffuser inlet section = 0.8 mm x 0.6 mm
Diffuser outlet section = 1.5 mm x 0.6 mm
Emitting nozzle-Diffuser nozzle distance = 6 mm

Figure 1 shows the final result of these tests as characteristic diagram of the pilot stage: the output pressure versus the supply pressure.

The maximum pressure recovered at the receiving nozzle is about 1500 Pa. The presence of the piezoelectic element reduces the maximun pressure recovered to about 1200 Pa, because of the partial occlusion of the exhaust section.

A numerical model of the air flux in the pilot stage was created to verify the behavior of the numerical calculation of compressible flow in a spatial geometry. The numerical model was defined by a Computational Fluid Dynamic (CFD) software package, FLUENT code, in which the Finite Volume Method is used to solve the numerical equations of the air flux in a spatial geometry.

The results of the numerical simulation were compared with the experimental ones as pressure drop at the receiving nozzle in steady flow conditions. A good agree was obtained between numerical simulation and experimental tests.

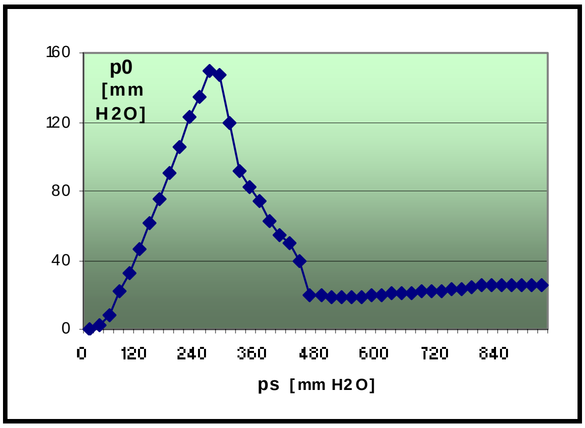


Figure 1. Output pressure po vs. supply pressure ps for the pilot stage

THE POWER SECTION

The three-way normally closed valve was designed using the operating principle of a flapper nozzle sensor. The supply pressure was fixed at 3 bar at this stage. The Fig. 2 shows a simplified drawing of the valve useful to understand the working principle of the valve, where p_c is the control signal arriving from the pilot stage. The upper part of the drawing shows the control diaphragm D_1, where the control signal p_c acts, that is a pneumatic amplifier. Under this diaphragm the power part of the valve is observable.

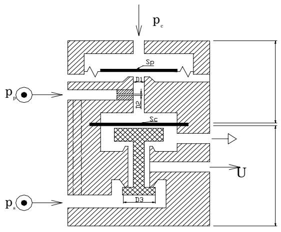


Figure 2. Simplified drawing of the power section of the valve

In the absence of the control signal p_c the supply air p_s, which reachs the volume between the power diaphragm D_2 and the control diaphragm D_1, via the d_2 diameter resistance and the d_1 diameter nozzle, flows to the exterior by a discharge port located below the diaphragm D_1. When the control signal p_c is applied, the control diaphragm D_1 closes the d_1 diameter nozzle and the pressure p_p rises stretching the power diaphragm D_2 and, moving, consequently, the flapper, leading to the switching of the valve.

The control diaphragm D_1 used was designed with the the pilot stage by Belforte et al. [2], while a design was made by the authors for the power diaphragm D_2. The design has considered two materials: silicone and natural latex. With silicone, different materials was used as internal structural part: cotton (thickness 0.75 and 1 mm), viscous synthetic tissue (t. 0.75 mm) and tulle (t. 0.75 mm). No structural part was used for natural latex. A technological set up was implemented to construct these diaphragms. Liquid silicone was degassed using a vacuum pump to prevent the presence of inclusions of air in the final diaphragms. Both silicone and latex based diaphragms were manufactured using an alluminium forming shape (Figure 3) and a slow flow-rate of iniection was adopted to avoid air inclusion in the texture of internal structural part.

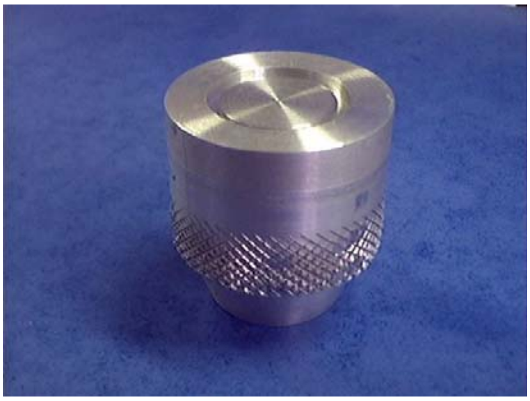


Figure 3. Diaphragm D_2 forming shape

All these diaphragms were tested at a pressure of 3 bar, measuring the displacement of the central point. Finally all of them were tested in the prototype of the valve. The Figure 4 shows the silicone-based diaphragm with internal cotton texture.

A theoretical scheme was used to define the focal sections of the valve, in order to ensure and to verify the static functionality of the system and to have also a valid tool to gain sensibility in realizing unforeseen behaviour of the valve. A concentrated parameters model was adopted. The approximation of concentrated parameters can reasonable be accepted because the ratio of conduit length against its diameter is not too large. Moreover the distance covered by a generic sonic pressure signal, for the duration of transitory of the valve switch, is much more larger than the same conduit. It can be noticed that neither capacitive nor inductive quantities are included in the scheme but it can be easily proved that these ones are not essential in steady-state conditions.

Figure 4. The silicone-based diaphragm

Boundary conditions for inlet pressure and outlet pressure are known, while some dimensions of internal restrictions were fixed to solve the above equivalent scheme.

The Fig. 5 shows the equivalent scheme of the power section of the valve

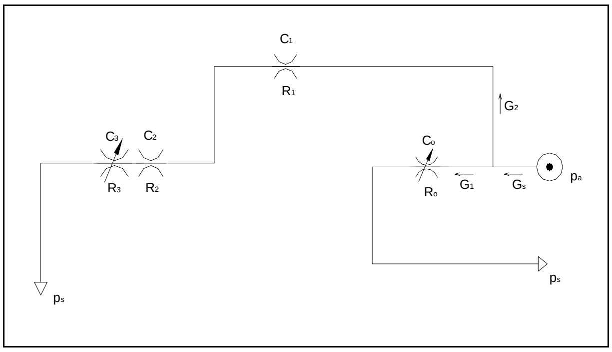


Figure 5. The equivalent scheme of the power section

Resistances R_0 and R_3 are represented as variable quantities, infact they are respectively associated to the power flapper nozzle and to the control flapper nozzle: their resistances can assume value ∞ (infinite), when the nozzle is closed by the flapper, or R_i. R_1 is the resistance of the restriction in the cylindric element, shown in Figure 6.a, below the power diaphragm D_2.

Solving the equivalent scheme, by using (1), (2), and (3) all the conductances of the pneumatic system are determinated:

$$R = \frac{\Delta p}{G} \quad (1)$$

$$C = \frac{1}{R} \quad (2)$$

$$G_1 + G_2 = G_s \quad (3)$$

$C_1 = 3.33 \cdot 10^{-12}$ m^3/(s Pa)

$C_2 = 3.43 \cdot 10^{-11}$ m^3/(s Pa)

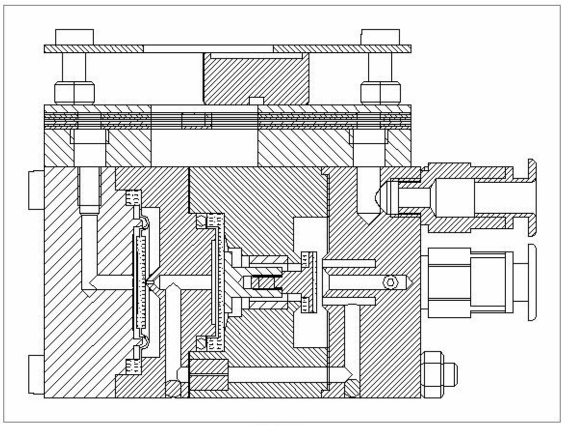
$C_3 = 3.53 \cdot 10^{-10}$ m^3/(s Pa)

About the flapper nozzle the goal was to obtain a high conductance and a good dynamic performance. The classical architecture of the flapper nozzle in a valve is formed by a circular hole, where supply air comes, that faces to the flapper. The idea was to use an annular shape of the hole that supplies air and a circular shape inside it bonded to the exterior. In this way the air flux flows to the exterior by two surfaces and it is possible to reduce the displacement of the flapper growing the dynamic performance of the valve.

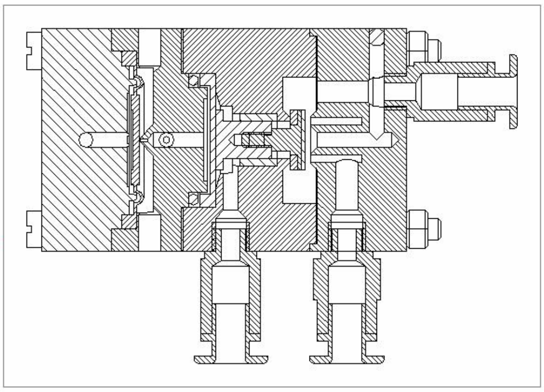
The Fig. 6 shows two sectional views of the designed valve, while in the Fig. 7 is shown the prototype manufactured.

In the upper part of the Fig. 6 a) the pilot stage is located. The connections on the right side are for the pressure supply of the pilot stage, in the upper part, and for the exaust of the power stage, in the lower part. From left to right in the Fig. 6 a) is possible to see four parts that represent the power section of the valve. The first part shows the air connection between the pilot stage and the power section of the valve. It is linked to the second part by the control diaphragm D_1. Continuing on the right side it is possible to see the power diaphragm D_2, between the second and the third part of the valve, that moves the spool, that's means the flapper, to close the nozzle. In the forth part it is possible to see the annular shape volume, connected to the air supplier in the bottom of Fig. 6 b) on the right, and the central hole that, together with the volume of the flapper, is connected to the exhaust port, on the right in the same figure. The material used for the power part of the valve is aluminium.

The Fig. 7 shows a photo of the prototype, where the pilot stage is on the top of the valve, while the power section is the lower part. In this figure you can see the fittings for air connection, and the electrical wires to command the piezoelectric element. Two of the 4 fittings are to be connected to the air supplier, 3 bar for the pilot and 3 to 8 bar for the power section. While the 2 fittings remained are the exhaust ports.



a)



b)

Figure 6. Sectional views of the valve: vertical section a) and horizontal section b)

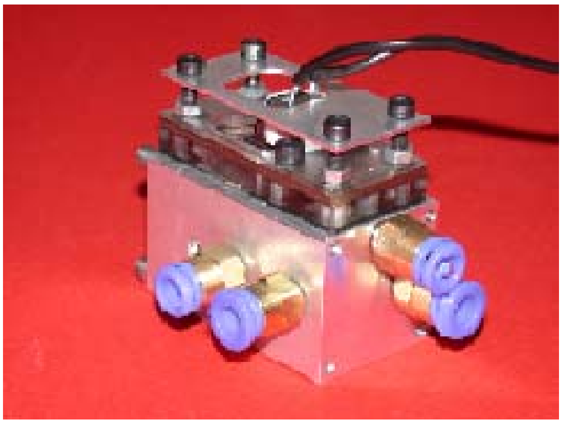


Figure 7. Photo of the valve's prototype

THE EXPERIMENTAL TESTS

Following the design and the manufacturing of the prototype of the 3/2 pneumatic valve, an experimental activity was defined to validate the design by calculating the main characteristic curves of the valve: the flow diagram inside the valve and the diagram of the step response test.

The flow diagram, shown in Fig. 8, was calculated following the international standard ISO 6358 [5] for three pressure values P_s before the valve: 3, 4 and 5 absolute bar. Also the valve's characteristic coefficients were calculated: C, conductance, and b, critical pressure ratio, Table 1.

For the step response test the international standard ISO12238 was followed [6]. In this case the valve was tested measuring the electric signal of the pressure transducer outside the valve versus time, so that the time delay of the valve can be calculated. A data acquisition board was used to acquire the signal both from the pressure transducer and from the signal generator used to send the command signal to the piezoelectric element. The electrical command signal for the piezo has an amplitude of 1 V and a frequency of 16.4 kHz in a square wave shape. The tests were carried out for the 5 different power diaphragm D_2 previously described. The results are shown in the Fig. 9 and the diaphragm in silicone with 1 mm of cotton has the shortest response time: 19 ms. This result confirms that the most rigid diaphragm gives the best dynamic performance at the valve. At this step no experimental tests are carried out on the fatigue life of the valve.

Table 1 Characteristic coefficients of the valve

P_S [bar]	C [dm3/(s bar)]	b
3	0.64	0.27
4	0.60	0.29
5	0.56	0.30

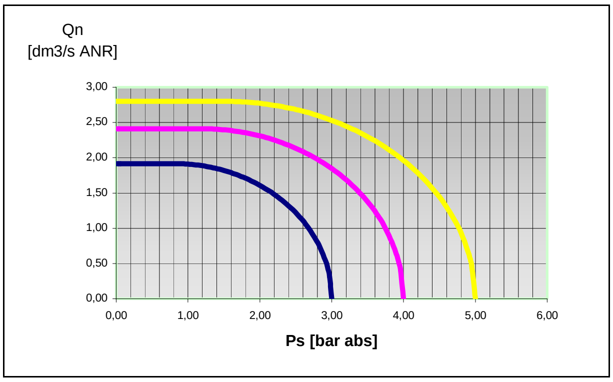


Figure 8. Flow diagram of the valve

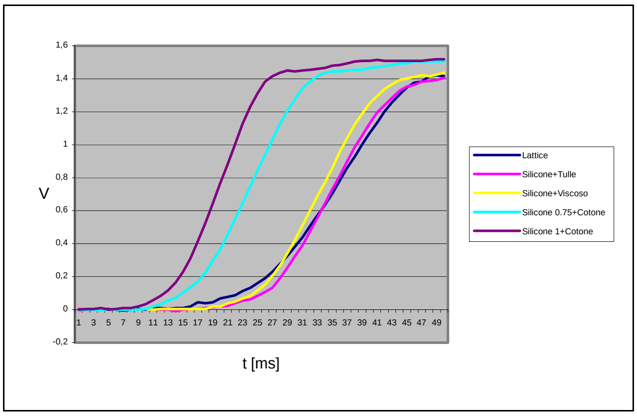


Figure 9. Step response tests for the different power diaphragms D_2

CONCLUSIONS

This paper presents the design and the construction of the power part of a 3/2 pneumatic valve that uses a low power pilot stage, based on laminar-turbulent transition of a fluidic jet. The valve can be used to drive a power stage of pneumatic circuits. The pilot stage uses an acoustic signal generated by a piezoelectric device to brake the laminar flow. The design of the power valve is presented. The prototype was constructed and tested. The results of the experimental tests has shown an interesting behaviour of the valve and confirm the design choices. Future work includes fatigue tests on the diaphragms D_1 and D_2 and on the complete valve.

REFERENCES

1. Belforte, G., Eula, G., Ferraresi, C., Viktorov, V. and Visconte, C. 2000. Optimization of a laminar-turbulent amplifier for electro-pneumatic interface. Flucome 2000, Sherbrooke, Quebec.
2. Belforte, G., Eula, G., Ferraresi, C., Viktorov, V. and Visconte, C. 2002. Integration of an electro-fluidic pilot stage in pneumatic valves. 3rd International Fluid Power Conference, Aachen.
3. Belforte, G., Manuello Bertetto, A., Raparelli, T. 1995. Back pressure sensor for very high precision measurement. ISMCR '95, Smolenice Castle, Slovakia.
4. Murrenhoff, H. 2002. Trends in valve development. 3rd International Fluid Power Conference, Aachen.
5. International Standard ISO 6358 Pneumatic Fluid Power. Component using compressible fluids. Determination of flow-rate characteristics, 1989.
6. International Standard ISO 12238 Pneumatic Fluid Power. Directional control valves. Measurement of shifting time, 2001.