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Pneumatic single flapper nozzle valve driven by piezoelectric tube

Abstract*. The article presents a construction, static testing and modelling of a single flapper nozzle pneumatic valve. Authors show testing of piezo tube PT230 which distinguishing feature is deflection in two directions. This testing is preliminary work in design of a novel electropneumatic valve. Studies have been performed on a special designed bench which consists of a pneumatic valve, which used piezo tube as a flapper. Data acquisition process and control were performed by dSPACE system. The preformed static pressure control tests, confirmed applicability of tube actuator in flapper nozzle type valves. Obtained results were compared with simulation model prepared in Matlab Simulink software.*

Streszczenie. *Artykuł zawiera opis konstrukcji, badania statyczne i modelowanie zaworu typu dysza przysłona. Autorzy zaprezentowali badania piezo rurki model PT230, której cechą charakterystyczną jest możliwość odkształcenia w dwóch kierunkach. Praca ta jest przygotowaniem do konstrukcji nowego zaworu elektropneumatycznego. Badania zostały wykonane na specjalnie w tym celu wykonanym stanowisku zawierającym zawór, którym zastosowano piezo rurkę jako przysłonę. Procesy akwizycji danych oraz sterowania wykonane zostały w systemie dSPACE. Przeprowadzone badania statyczne sterowania ciśnieniem wyjściowym, potwierdzają możliwość zastosowania piezo rurki w zaworach typu dysza przysłona. Zarejestrowane wyniki poddano porównaniu z modelem przygotowanym w oprogramowaniu Matlab Simulink.*
(Zawór pneumatyczny typu dysza przysłona z rurką piezoelektryczną jako elementem zadającym)

Keywords: flapper, nozzle, piezoelectric tube, pressure control.
Słowa kluczowe: przysłona, dysza, piezoelektryczna rurka, sterowanie ciśnieniem.

Introduction

Advanced electronic control in fluid power had its beginning with development of servo valve technology in forties of last century. One of developed type of servo valves are flapper nozzle type amplifiers [1][1][2]. The most advanced part of these valves is a torque motor, which transduces an electric energy to angular movement. This mechanical movement (displacement of the flapper), is responsible for control of an fluid amplifier named cascade. It consists of a constant pneumatic resistor (orifice) and a variable pneumatic resistor (flapper nozzle pair) – Fig. 1. Thanks to large amplification its allow to convert a small flapper movement in to a pressure differential signal, used for spool position control in a second stage of valve, or another receiver e.g. piston. High control accuracy and good dynamics of these valves are obtained through complex design and close manufacturing tolerances. High price, complex design and calibration process, sensitivity to external magnetic field, are the main disadvantages of this solution [1]-[4]. Because of this many efforts in designing new types of valves without torque motor, has been made for years.

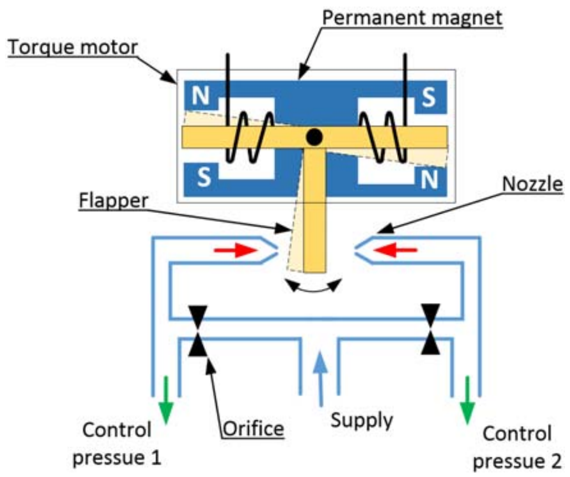

Fig.1. Schematic of a nozzle flapper one-stage servo valve

In this field it is also possible to replace the torque motor with structures which are based on smart materials. Usually purposes of such replacement are improvements of operating parameters (e.g. dynamics, energy consumption), or design (e.g. less weight, seize). Smart materials are able to change their properties (e.g. shape), under external stimulus. As a kind of stimulation should be mentioned: electric field (piezoelectric based materials), thermal changes (thermal shape memory alloys), and magnetic field (magnetostrictive materials, magnetic shape memory alloys) [5][6]. Common feature of these materials is wide hysteresis loop which forces application of closed loop control systems.

Using thermal shape memory alloys it is possible to put them in design of bistable safety valves. These valves are used as cut off valves for exhaust gases during fire when temperature rises rapidly [7]. Second group of application are flow control valves. Interesting designs are described in [8][9]. In both cases SMA wires deflect spring causing valve opening. Elasticity force closes valve, when temperature decreases. Disadvantage is low dynamics because thermal processes are distinguished by high time constants. It should also be noted that these valves are simple designs.

Magnetic shape memory materials are new very interesting group of active materials which combine great strains and good dynamics. Preliminary proposals contain design of proportional throttling valves and proportional pressure controllers [10][11]. Design and research of one stage pneumatic throttle valve are described in [12]. Very close to this design is valve with dielectic elastomer [13].

Among scientists the most popular group of active materials which are used in fluid power technology are piezoelectric based materials. Mainly hydraulic two stages servo valves are under investigations, because many piezo samples are very similar in shape to flapper (easy replacement). Despite the fact that piezo materials are distinguished by small deformations range it is enough to operate successfully between two nozzles in first stage of servo valve [14-18] Also in jet deflector hydraulic amplifier piezoceramics was applied [19]. In proportional flow control valves piezo stacks are used instead solenoids directly connected with spool [20][21]. Two very similar designs are presented in [22][23], where classical flapper with flexure tube is deflected by piezo and magnetostrictive transducers.

Smaller group are pneumatic pressure control valves as well as in this area piezoceramics is used. In design [24][24] piezo stack moves elastic flapper in single nozzle system. Another paper shows [25] full cascade where flapper (clearly longer), is placed between two piezo-benders.

A distinguishing feature of all mentioned solutions is application of piezoelectric materials which strain only in one direction. Since the first efforts have been made in application of piezo bender in flapper nozzle valves, new types of piezoelectric materials have been developed. Interesting type of piezoelectric materials are materials which can deflect in more than one direction, e.g. 2D piezo benders or piezo tubes. The piezoelectric tube was invented in 1986 and found application in scanning tunnelling microscopy and scanning force microscopy. Scientific papers which refer to these material are focused mainly on position control [26][27].

The researched material was a PT230 tube developed by PI Ceramic. The actuator has four electrodes, distributed on the circumference of the tube, used for 2D motion control of the free end of the actuator. The fifth electrode is located on the inner side of the tube and used as common ground. Supply voltage was applied directly to the electrodes (Fig. 2).

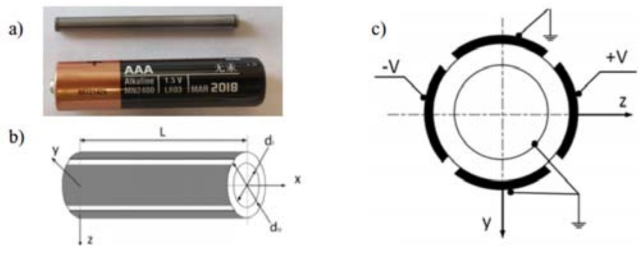

Fig.2. Piezoelectric tube a) PT230, b) dimensions,c) electric connection schematic

Because of the ability of these materials to deflect in two directions, application of these piezo elements can entail new features and capabilities of classic valves. This paper is a first attempt to application of these materials in design of pneumatic valves.

Test rig and design of a piezoelectric flapper nozzle valve

The test rig consists of: pneumatic valve, manifold, data acquisition system and piezoelectric power supply system. The presented valve contains a body with build in pneumatic restrictors, and piezoelectric tube mounting bolted to it. The body is connected to the manifold. The valve body includes an orifice placed on the supply side, control output port and a variable restrictor as a nozzle-flapper (piezoelectric tube) pair – Fig. 3. The inlet orifice has a constant diameter, and can be easily replaced whit another one. Similarly the output nozzle was connected to a mounting, which was equipped with fine thread. This solution allows to bring the nozzle closer to the flapper, with a high precision of 0,5 mm for a turn. In the volume between the inlet and outlet, control pressure varies depending on the actual position of the flapper (in reference to the nozzle). The control volume was reduced to minimum and is similarly like in two stage valves. The flapper was performed as a cuboid in the 3D printing technology, and glued at the free end of the piezoelectric tube. The tube was glued in mounting as it shown in Fig.3 and indicated as number 1 in Fig. 5. The valve was bolted to the manifold, which consists of a number of drillings enabling air supply and control pressure measurement. All most important connections were sealed with O-rings.

The block scheme of the test rig is presented in Fig. 4 and the photo in Fig. 5.

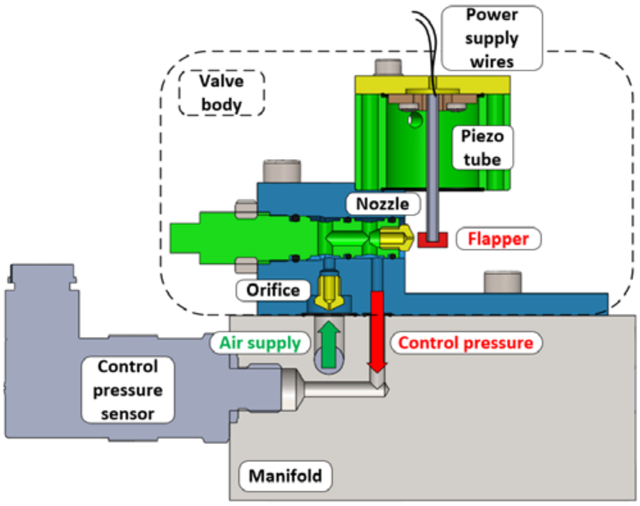

Fig.3. Schematic configuration of the piezo valve system

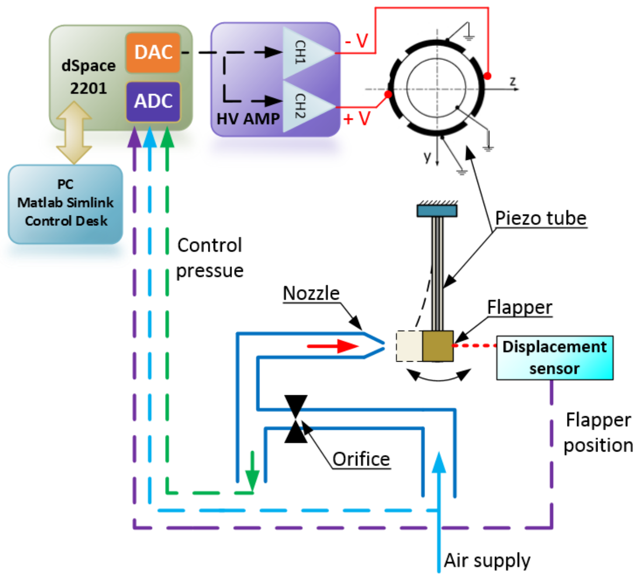

Fig.4. Schematic of designed nozzle flapper valve and test rig

The test rig was equipped with two pressure transducers. First one (WIKA A-10), measures the supply pressure (9 in Fig. 5). This measurement is preform to exclude the influence of the supply system on the performance of the amplifier. The second sensor measures the control pressure, and it is a precise WIKA S-10 transducer. The supplied air pressure is adjusted via SMC IR2020 pressure regulator (8 in Fig. 5).

To control and power supply of the piezoelectric tube actuator a high voltage amplifier was designed. The device consists of: AC transformer, DC rectifier with filtering, and two PA91 (APEX) power amplifier modules (no. 4 in Fig. 5). The gain of each channel can be set separately. For the purpose of this work the gain was set to 20, due to the ratio of input and desired output signal. The amplifier was supplied by an autotransformer (no. 5 in Fig. 5) connected to the power grid.

The whole control system used to drive piezo works under Matlab Simulink and dSPACE DS2201 ADC/DAC converter cards (no. 6, 7 in Fig. 5). Matlab model was used to generate signals and get measurement data. Output signals from DAC card were directly connected to voltage amplifier. One of the signals was inverted in order to obtain two voltages supply signals with opposite polarity. ADC card was used to collect and register signal from displacement and pressure sensors. Created system works in real time mode under Control Desk dSPACE software, where all parameters from Simulink model can be changed continuously. The piezo displacement was measured with Fiberoptic D63 laser sensor (no. 2 in Fig. 5).

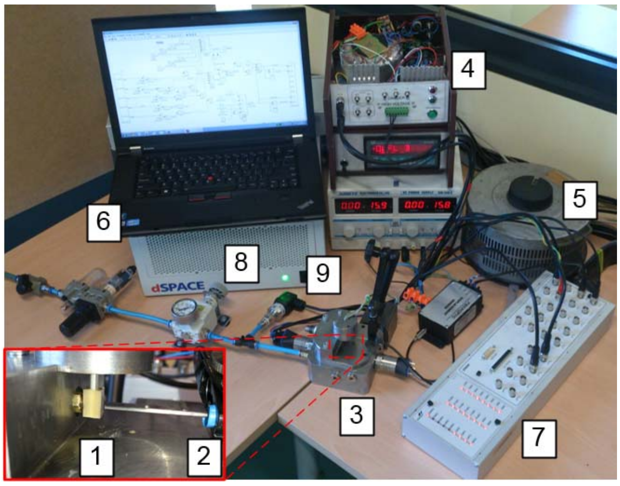

Fig.5. The test rig and piezo valve

Piezoelectric tube test

In order to study the basic properties of the piezoelectric material, an open control positioning study was performed. The study was conducted on the above-described test stand, with two opposite electrodes energized, while the remaining electrodes are connected to ground. In this configuration the free end of the tube bends along the Z axis. The electrical connection is shown in Fig. 2. c). The geometrical parameters of the tube are: length L = 40 mm, outer diameter d_o = 3.2 mm, inner diameter d_i = 2.2 mm. The piezoelectric charge constants for the actuator d_{31} = -180e-12 C/N and the operating voltage is ± 250 VDC. The displacement of the free end of the tube was measured in response to different voltage values and the results can be seen in Fig. 6. This figure shows that the relationship between voltage and displacement is not linear. The test material also exhibits a hysteresis of approximately 20%.

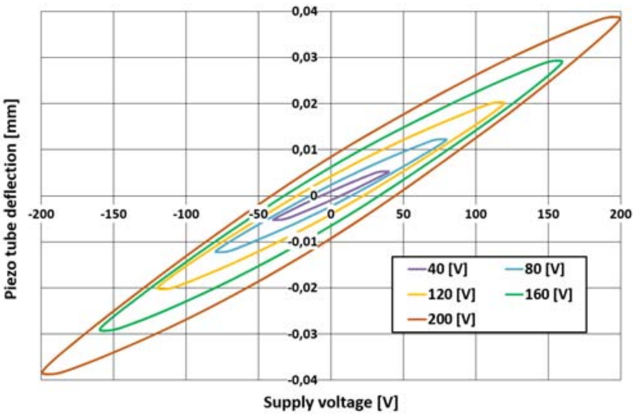

Fig.6. Piezo tube test results

Measurement Results

The core idea of the experiments was confirmation of application possibility of the piezo tube actuator in pneumatic flapper nozzle valve. To examine this possibility the piezo tube was used to drive a single nozzle flapper valve. This allowed to measure the piezo flapper position during the investigation. In order to demonstrate the range of pressure controllability several experiments were performed. The tests were divided in two phases. In the first test, a mechanical flapper with position adjustment via micrometer screw was used. This test shows the complete pressure regulation range. The second test consists of a pressure control using piezo tube as a drive.

The tests were repeated for two different sets of orifice and nozzle diameters. All tests were performed on test rig described earlier in this work. The maximum air pressure was 3 bar, and the maximum piezo voltage supply was set up to 200 VDC.

The tests shown in Fig. 7 and 8 were performed for the first set, which contains an orifice with diameter 0.52 mm and nozzle with diameter 1.75 mm. The first (Fig. 7), test is a quasi-static characteristic of the valve driven by a mechanical flapper. The test was preformed from closed nozzle position (control pressure is equal to supply pressure), and ends when no changes in output pressure appears. This test shows the full characteristic of the valve for three different supply pressures. The results shows distinctive shape of flapper nozzle amplifier characteristic. Initial and end nonlinearity is connected with a linear pressure control part.

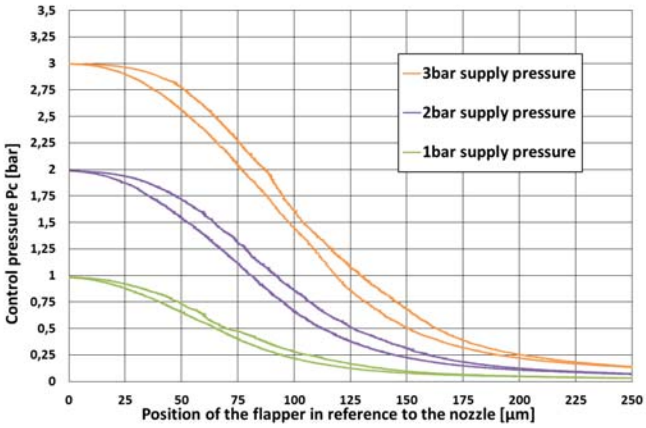

Fig.7. Pressure regulation of the valve driven by a mechanical flapper

The next step in the investigations was obtaining the characteristics possible to achieve by piezo tube flapper. The initial flapper position in reference to the nozzle was adjusted to minimalize the leakage and get the best valve operating range for supply pressure 1 bar.

The control signal for piezo tube was a sinus wave, frequency of 0.05 Hz and amplitude from 1 to -1 V, which suits to supply voltage of the piezo from -200 up to 200 VDC. The Fig. 8 shows the test results of piezo driven valve. The influence of the air flow force on the flapper depending of the pressure supply, can be seen on the piezo movement range. For 1 bar of supply pressure the piezo moves at full range. In case of increasing the supply pressure the displacement decreases.

Comparing the test results of mechanical and piezo driven flapper, a pressure controllability of the piezo valve can be seen in Fig. 9. Increase of supply pressure causes increasing of air leakage and pressure drop, because the piezo tube is bended at initial position. Furthermore the plots for different supply pressures are shifted in reference to each other, because of existing of the force resulting from air flow. As can be seen the piezo pressure plots are not in the full linear range of the valve pressure controllability.

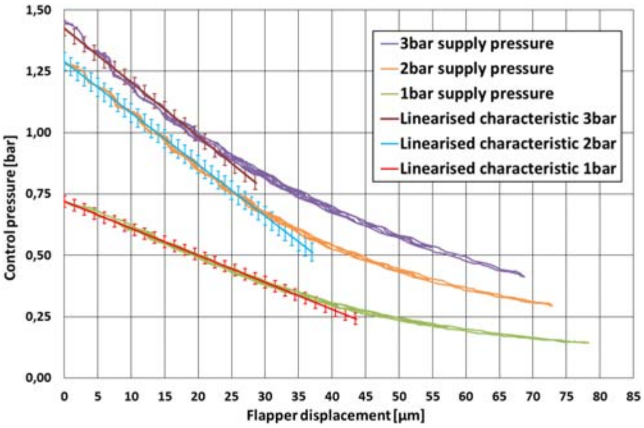

Fig.8. Pressure regulation of the valve driven by a piezoelectric flapper

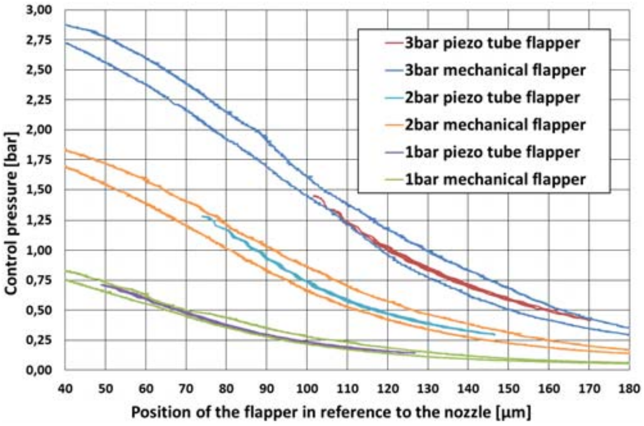

Fig.9. Comparison of mechanical and piezo driven valve tests results

To reduce the flow force and expand the piezo pressure controllability range, a new diameters of orifice and nozzle were applied. The mechanical and piezo tests described above were repeated for orifice diameter 0.2 mm and nozzle diameter 0.92 mm. The test using a mechanical flapper driven by a micrometer screw was performed with lower velocity to receive more static results. Because of manual control ragged characteristic was received.

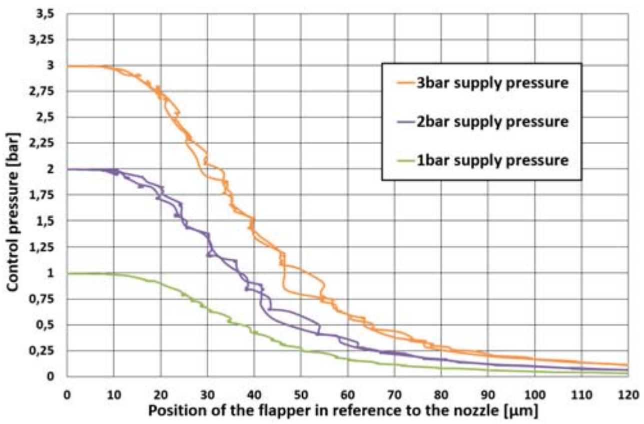

Fig.10. Pressure regulation of the valve driven by a mechanical flapper

The Fig. 11 shows the test results of piezo driven valve. The influence of the air flow force on the piezo tube movement range was not noticed. Moreover a significant expand of pressure controllability range was observe.

Comparing the test results of mechanical and piezo driven flapper valve (Fig. 12), an increase of control range of the piezo valve can be seen. The extended control scope was achieved by decreasing of air flow force on the flapper.

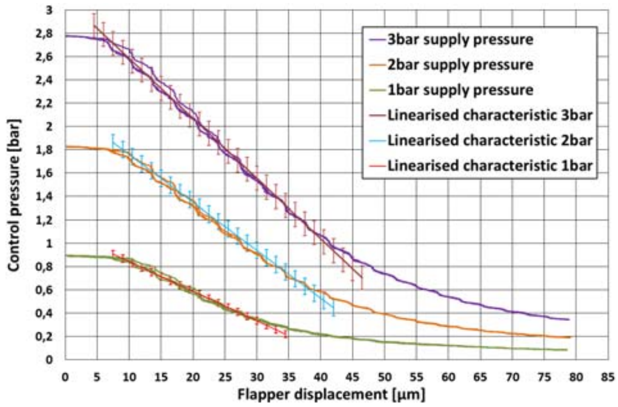

Fig.11. Pressure regulation of the valve driven by a piezoelectric flapper

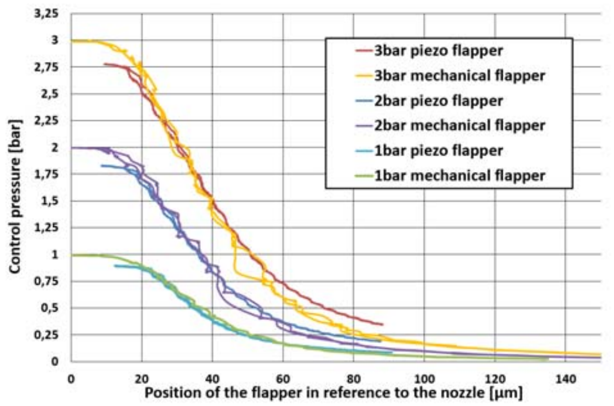

Fig.12. Comparison of mechanical and piezo driven valve tests results

In the Fig. 8 and 11 linearized characteristic were added to show the linear range of pressure control. The linearised characteristic was adjusted to the origin characteristic nonlinearity error do not exceed 5% in whole range. The obtained linear control range and sensitivity (slope of the linearized characteristic) were compared in the table 1.

Table 1. Valve performance comparison for both diameters sets

Parameter	Unit	Set 1	Set 2
Orifice diameter	[mm]	0.52	0.20
Nozzle diameter		1.75	0.92
Ratio of the pressure control range of the valve to supply pressure			
for supply pressure 1 bar	[%]	56.9	81.2
2 bar		49.3	81.9
3 bar		34.5	81.2
Sensitivity (slope) of the linearized characteristic			
for supply pressure 1 bar	$\left[\frac{kPa}{\mu m}\right]$	1.1	2.55
2 bar		2.1	4.1
3 bar		2.2	5.15
Ratio of the linear pressure control range of the valve to supply pressure			
for supply pressure 1 bar	[%]	47.9	68.9
2 bar		37.8	55.2
3 bar		20.9	46.4
Parameter	**Unit**	**Set 1**	**Set 2**
Flapper movement range for the linearized characteristic			
for supply pressure 1 bar	[µm]	43.5	27.9
2 bar		36	34.5
3 bar		28.5	27

Pneumatic model of the valve

In case of improve the future valve design an attempting to pneumatic modelling of the valve was performed. First approach to pneumatic modelling of the valve was simplification of pneumatic compression phenomena. It is assumed, that the environment parameters like ambient temperature and pressure stay constant. This allowed to make dynamic approach of model building. Detailed pneumatic equations, widely used in literature [28][29], are very complex.

(1) $$q_{mw}=C_wA_w\frac{p_0}{\sqrt{RT_0}}\sqrt{2\frac{\kappa}{\kappa-1}\left(\beta_w^{\frac{2}{\kappa}}-\beta_w^{\frac{\kappa+1}{\kappa}}\right)},\beta_w\geq 0.528$$

(2) $$q_{mw}=C_wA_w\frac{p_0}{\sqrt{RT_0}}\sqrt{\kappa\left(\frac{\kappa}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}},\beta_w<0.528$$

where: q_{mw} – mass flow, C_w – flow coefficient, A_w – nozzle area, p_0 – supply pressure, R – gas constant, T_0 – supply temperature, κ – adiabatic coefficient, p_a – ambient pressure, $\beta_w=\frac{p_a}{p_0}$

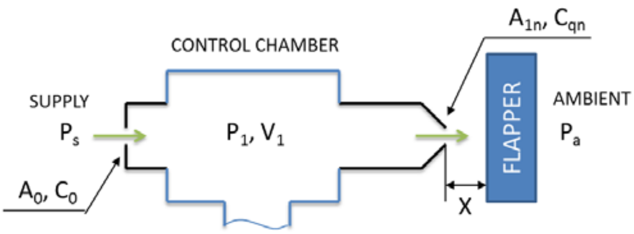

Fig.13. Schematic of nozzle flapper valve

Achieving full dynamic model, aforementioned formulations (1), (2), is very complicated task. It is intended to build dynamic model of the valve in near future. Therefore simplified dynamic pneumatic model was used in this research [17] (Fig. 13).

(3) $$\dot{P}_1=\frac{\beta}{V_1}\sqrt{\frac{2}{\rho}}\left[C_{q0}A_0\sqrt{(P_s-P_1)}-C_{qn}A_{1n}\sqrt{P_1}\right]$$

where: P_1 – control pressure, $\dot{P}_1$ – derivative of control pressure, β – bulk coefficient, V_1 – control pressure chamber, ρ – air density, C_{q0} – orifice flow coefficient (constant), A_0 – orifice area (constant), P_s – supply pressure, P_1 – control pressure, C_{qn} –nozzle flow coefficient, A_{1n} – nozzle area (variable).

This model was initially validated with static characteristics. Authors have not considered the dynamics so far. Matlab-Simulink model is presented in figure 14.

In pneumatic models of nozzles or orifices exist unknown flow coefficient, which should be set experimentally. The mentioned coefficient is not constant and varies relative to e.g. flow value, flow character, Reynolds number, differential pressure. The relations could be simplified to only one, that flow coefficient is dependant from the flapper nozzle distance. Obviously this simplification is correct only with assumption that environment conditions do not change. The variations of the nozzle flow coefficient, obtained in the experiment with set 1 (described above), are shown in the figure 14.

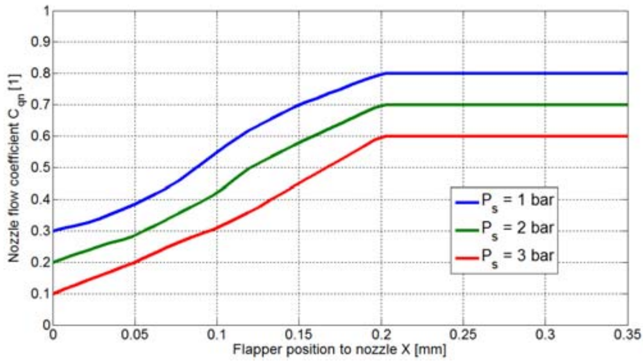

Fig.15. Variation of flow coefficient C_{qn} for different supply pressure values

The flow coefficient values C_{qn} for nozzle was obtained manually. Noticeable is the fact, that only one flow coefficient was modified, while the orifice flow coefficient C_{q0} remained constant and equalled 0.92. The flow coefficient C_{qn} was initially set for results with 2 bar of supply pressure, but it was necessary to modify the values for different supply pressure values. It can be seen that the characteristics change proportionally to value of the supply pressure. Similar coefficient characteristic was prepared for experiment with set 2. The results of C_{qn} adaptation are in the figure 16.

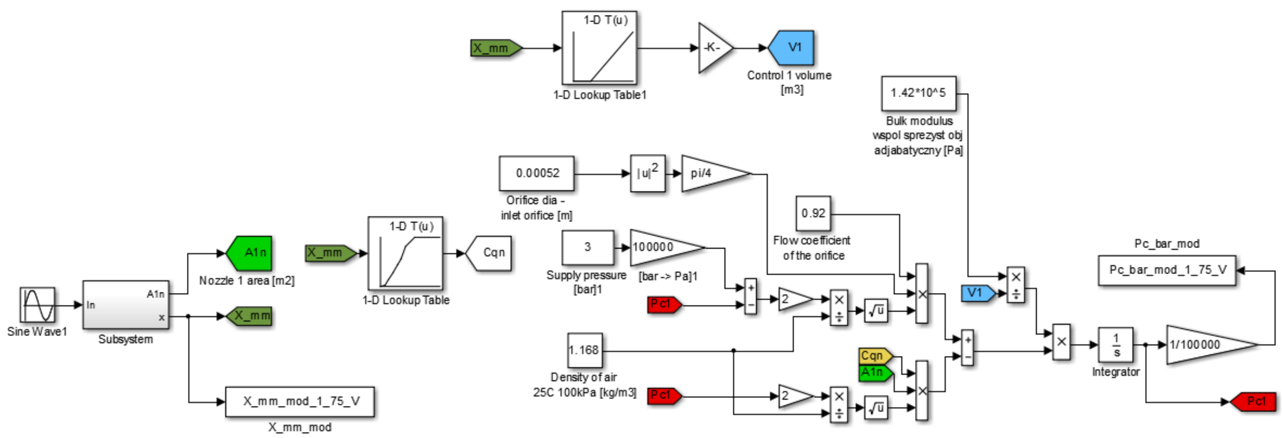

Fig.14. Matlab-Simulink simplified pneumatic model

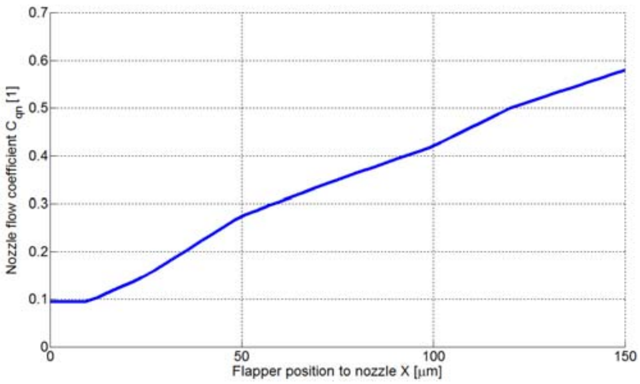

Fig.16. Variation of flow coefficient C_{qn} for different supply pressure values

Comparison of described model and measurement data are presented in figure 17 and 18.

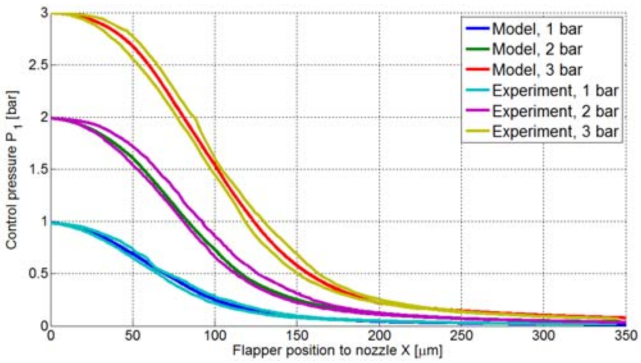

Fig.17. Comparison of mechanical driven valve tests and modelling results for diameter set 1

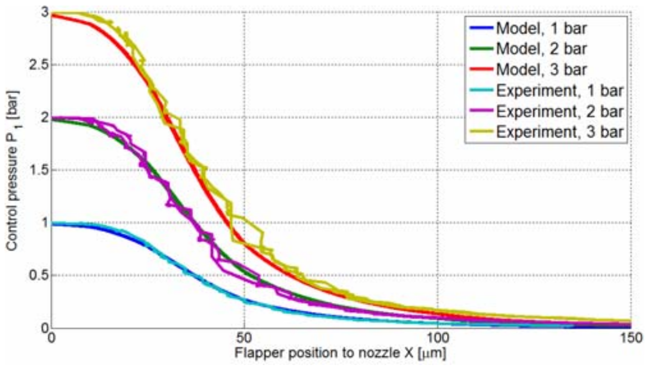

Fig.18. Comparison of mechanical driven valve tests and modelling results for diameter set 2

Very important is remark that ranges of effective flapper movement for set 1 and set 2 are different. Therefore C_{qn} coefficient saturate for set 1. The saturation effect of adapted C_{qn} could be caused by reaching sonic flow in the nozzle, which limits flow value. The result is that change of the flapper nozzle distance after critical value does not have influence on the output control pressure. Another important note is that experiment with set 1 was performed as first, under quasi-static conditions. This is the reason, why in static characteristic occurs dynamic hysteresis. It was assumed that the true static characteristic is the middle line between hysteresis loop lines. The model parameters (C_{qn}) was adopted to that middle line. The dynamic phenomena could be the distortions that cause C_{qn} parameter is dependent on supply pressure value P_s. The experiment results from set 2 shows less dependency of the supply pressure, probably because these measurements was performed statically. Last remark is the fact that important is the starting point of the characteristic, when the nozzle is closed. It is difficult to obtain fully closed nozzle. The nozzle has little leakage or the flapper is strongly pressed to the nozzle, which in normal work could never happen. This is the problem of irregular surface of the nozzle forehead and flapper side.

Conclusions

The presented results focus on the problem of application of piezoelectric tube in flapper nozzle pneumatic valve type. This type of piezo material have not been used in fluid technology so far. Design of a single flapper nozzle valve was proposed and tested for two different sets of restrictors. The results compared in the Table 1 show, that the piezo driven valve performance can be easily adjusted by changing the pneumatic cascade parameters. The end results for the second parameter set show good pressure controllability range of above 80% of supply pressure. A linear pressure control range of about 69% and sensitivity of 2.55 kPa/μm for one bar was achieved. Connecting this with high deflection accuracy of the piezo tube actuator the results are promising for the future research. Referring to the Table 1, it can be seen that usage of orifice and nozzle set 2 results more predictive valve parameters. For example the sensitivity and linear range of the valve are approximately proportional to supply pressure, while the flapper displacement and pressure range are similar for all supply pressure values. The reason for that could be different values of air flow forces acting on the flapper for each used set. Therefore the set 2 is better for future research.

The tests were a first approach to confirm applicability of this type of material in pneumatic valves. The performed tests were only static and because of this further dynamic studies need to be carried out.

Static pneumatic model of the valve was proposed, and the theoretical results were compared to the real one. The comparison shows good accuracy of the theoretical model and will be used in the future to design a new valve.

Centre of concern of following research of the valve design will be application of piezo tube material in valves with more than two nozzles. It will allow to fully utilize all possibilities of this material and to design valves with more possibilities.

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