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ANALYSIS OF THE MATERIAL AND THE ACTUATOR INFLUENCE ON THE CHARACTERISTICS OF A PNEUMATIC VALVE

ANALIZA VPLIVA MATERIALA IN AKTUATORJEV NA LASTNOSTI PNEVMATIČNEGA VENTILA

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Development of pneumatic valves dictates improvements in the area of valve miniaturization, lower price, better dynamic characteristics and lower consumption of electric energy which can hardly be achieved with commonly used electromagnetic actuators. This is also the reason why alternative actuators started to appear on the market, among them piezo actuators which offer the best possibilities for practical use in pneumatic valves. The article treats the analysis of dynamic characteristics of an ISO 3 5/2 directional pneumatic valve for different parameters. The influence of three different piston materials on the valve reaction and response time is analyzed, showing the influence of the mass of moving parts on valve dynamics. A special emphasis is given to the analysis of the actuator energy consumption for a pneumatic valve actuated by an electromagnetic actuator in one case and by a piezo actuator in another case during only one switch. The results obtained from the analysis indicate that the material of moving parts (piston) influences significantly the dynamics of the valve. Experimental results prove that the lower the mass, the faster is the displacement of the valve piston, and consequently, the switchover and the response time of a pneumatic valve gets shorter. The analysis has shown that the valve, actuated by a piezoelectric actuator consumes much less electric energy than the valve, actuated by the electro magnets and also achieves better dynamic characteristics.

Key-words: pneumatic valve, electromagnetic actuator, piezoelectric actuator, energy consumption, dynamic response

Razvoj pnevmatičnih ventilov narekuje izboljšave na področju miniaturizacije, nižjih cen, boljših dinamičnih lastnosti in nižje porabe električne energije, kar pa je zelo težko doseči z običajno uporabljenimi elektromagnetnimi aktuatorji. Zaradi tega so se na tržišču začeli pojavljati alternativni aktuatorji, med katerimi nudi največ možnosti za praktično uporabo v pnevmatiki piezo aktuator. Prispevek obravnava analizo dinamičnih karakteristik pnevmatičnega potnega ventila ISO 3 5/2 za različne parametre. Analiziran je vpliv treh različnih materialov bata na odzivnost in odgovor prehoda ventila, ki prikazuje vpliv mase gibalnega elementa na dinamiko ventila. Poseben poudarek je posvečen analizi porabe električne energije za pnevmatični ventil, ki je krmiljen v enem primeru s piezoelektričnim aktuatorjem in v drugem primeru z elektromagnetnim aktuatorjem za čas enega preklopa. Rezultati, pridobljeni iz meritev kažejo, da material gibalnega elementa (krmilni bat) občutno vpliva na dinamiko ventila. Eksperimentalni rezultati so dokazali, da manjša kot je masa krmilnega bata, krajši je čas pomika ventila in posledično je preklopni čas, ter čas odgovora prehoda pnevmatičnega ventila krajši. Analiza je tudi pokazala, da porabi ventil, krmiljen s piezoelektričnim aktuatorjem, precej manj električne energije kot ventil, krmiljen z elektromagnetnim aktuatorjem, poleg tega pa doseže tudi boljše dinamične lastnosti.

Ključne besede: pnevmatični ventil, elektromagnetni aktuator, piezoelektrični aktuator, poraba energije, dinamični odziv

1 INTRODUCTION

Design and development of pneumatic valves constantly dictates improvements in valve miniaturization, lower price, better dynamic characteristics and lower consumption of electric energy [1,2,3,4]. Better dynamics of valves can be achieved with use of light-weight piston materials and alternative actuators for their actuation. The most commonly used actuators in industry are electromagnetic actuators which are robust and reasonably priced, however, they are questionable when shorter switchover and response times are needed, which is desirable in high dynamic systems. Shorter switchover and response times occur due to magnetic induction and eddy current when switching the current on. With the use of alternative actuators, among which piezoelectric actuators offer the best possibilities for practical use [4,5,6,7,8,9], much shorter response times and lower electric energy consumption can be achieved. On the one hand, switchover times of the electromagnetic actuators lie in the range between 10 to 20 ms, whereas on the other hand, piezoelectric actuators achieve shorter switchover times in the range of 500 µs [3]. For consumers also the switchover repeatability in the whole life time of a valve is of great importance.

Today's valve pistons are made of steel for hydraulic valves and of aluminium for pneumatic valves and they are known for their relatively high density (especially those, made of steel), which influences negatively the valve dynamics, especially the response time. The lower are the masses of moving parts, like pistons and electromagnetic coils, the shorter is the switchover time and the dynamics is better [10].

A piezoelectric actuator works on the principle of the inverse piezo effect. It converts electric energy directly to mechanical energy, while the electromagnetic actuator converts electric energy indirectly to mechanical energy

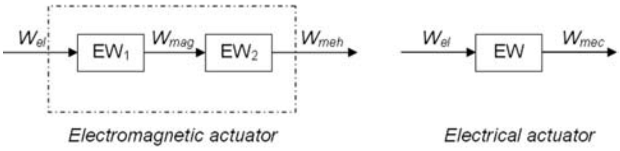

Figure 1: Conversion of electric energy to mechanical energy for electromagnetic and piezo actuator
Slika 1: Pretvorba električne energije v mehansko za elektromagnetni in piezoaktuator

(**Figure 1**). Because of the indirect energy conversion, longer response times are achieved with electro magnets and consequently, worse dynamic characteristics of a pneumatic valve are obtained [3,5].

2 PIEZOELECTRIC ACTUATOR

In 1880 it was discovered that electric potential could be generated if pressure is applied to quartz crystals (piezoelectric material). This is called piezo effect. Vice versa, if electric potential is applied to piezoelectric material it changes its shape – inverse piezo effect. Piezo effect exhibited by natural materials as quartz, tourmaline, Rochelle salt etc. is very small so new materials with improved characteristics of piezo effect were developed. These materials are polycrystalline ferroelectric ceramic materials such as barium titanate and lead (plumbum) zirconate titanate (PZT), which is also a most widely used material for actuator applications today [11].

The biggest advantages of piezoelectric actuators over electromagnetic actuators are short response time and low energy consumption in the stationary state. Other advantages and also disadvantages are presented in **Table 1** [5,11,12]. Extension of these actuators is proportional to the applied voltage.

Table 1: Properties of piezoelectric actuators
Tabela 1: Lastnosti piezoelektričnih aktuatorjev

Advantages	Disadvantages
High resolution	Hysteresis
High force generation	Drift (Creep)
Good efficiency	Small strain (0,1-0,2 %)
High dynamics – fast expansion	
No wear (no moving parts)	Problem of depolarization
High material stiffness	
Low power consumption (stationary state)	High supply voltage (60–1000 V)
Operation at cryogenic temperature	
No magnetic field	

Two main types of piezo actuators on the market are stack piezo actuators and bending piezo actuators (**Figure 2**). Main properties for selecting the right piezo actuator for a particular application are: force generation, deflection, dimensions and response time. Stack actuators (**Figure 2a**) can consist of monocrystal or of several piezoceramic plates. An advantage of the construction out of several plates is that a lower voltage is required for supplying the stack actuator, which is especially important for applications in fluid power technology and in assembly automation. They also generate high forces up to several tons but have small deflection – several 100 μm [11]. A bending actuator usually consists of a passive metal substrate which is glued to a piezoceramic strip – bimorph actuator [11]. There are also bending actuators with several layers – trimorph or multimorph. A bending piezoelectric actuator has high deflection – greater than 1 mm but generated forces are very low, only several *N*. For the operation of a pneumatic valve two types of piezoelectric bending actuators can be chosen (**Figure 2**):

- Cantilever piezo element (**Figure 2b**)
- Crossbow piezo element (**Figure 2c**)

The bending cantilever piezo element is fixed only at one end; it has higher deflection and smaller forces than the crossbow piezo element. The crossbow piezo element is fixed on both ends [3,13].

3 TEST RIG

A test rig (**Figure 3**) was set up to carry out the measurements of the valve characteristics. Measurements were performed on a modified directional pneumatic valve ISO 3 5/2 which has a maximum nominal flow of 3539 L/min. Actuation with a piezoelectric actuator was

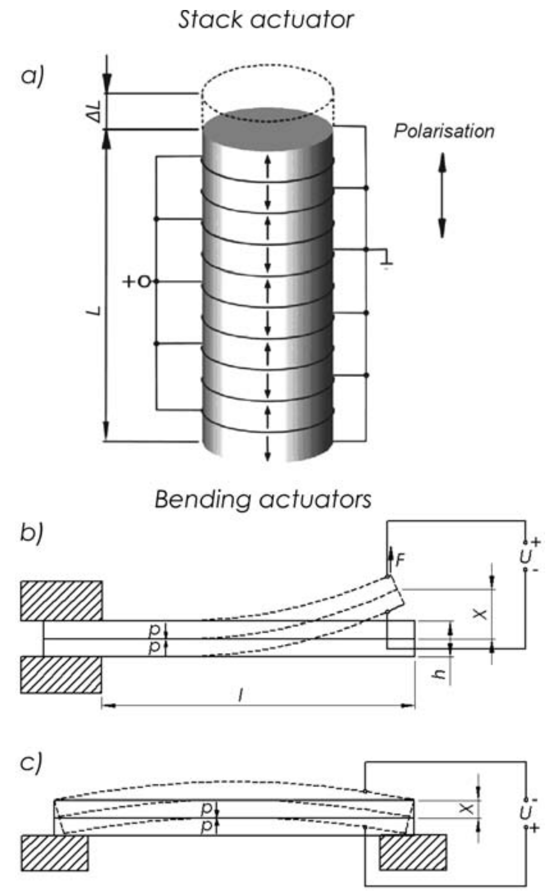

Figure 2: Different types of piezoelectric actuators
Slika 2: Različni tipi piezoelektričnih aktuatorjev

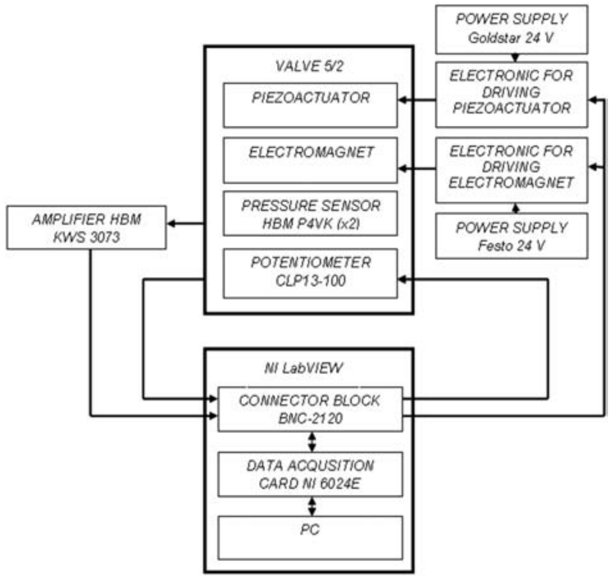

Figure 3: A block diagram of the test rig
Slika 3: Blokovni diagram preizkuševališča

performed using the nozzle/flapper principle (**Figure 4**) [3,14].

The pneumatic valve was actuated with the electromagnetic actuator in one case and with the piezoelectric actuator in the other case. In both cases the energy consumption was analyzed. The analysis was made for a single switchover when the actuator should hold the given position for one hour.

To represent the influence of the matereial of the moving part, i.e. valve piston, on the valve dynamics, three different piston materials were used:

- Aluminium piston (commonly used in pneumatic)
- Steel piston (commonly used in hydraulics)
- Light-weight material piston

Using the LabView program package, the following parameters (signals) from the test rig were measured and analyzed:

- Pressure in both chambers

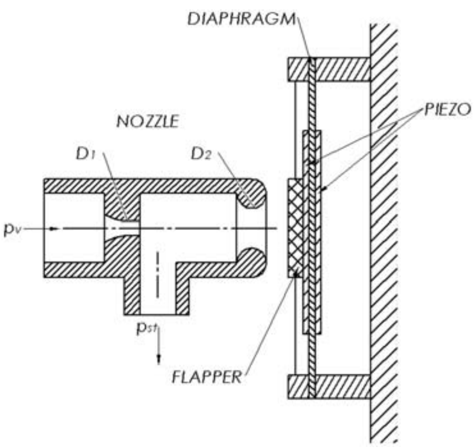

Figure 4: Nozzle/flapper principle
Slika 4: Princip šoba/odbojna plošča

- Stroke of the valve piston
- Energy consumption of the actuator

The pressure in each chamber of the valve was measured with a piezo pressure gauge HBM P4VK, and the voltage signal was then amplified with an HBM KWS 3073 amplifier. The stroke was measured with a CLP13-100 potentiometer, which was supplied from a BNC-2120 shielded block, and the energy consumption was measured with special electronics, designed for powering a piezo-electric and electromagnetic actuator. All the signals were brought to a BNC-2120 shielded connector block which was connected to a 6023E card for acquiring signals in the PC.

4 RESULTS

In order to analyze the dynamic characteristics of valves, the amplitude and phase diagram are used – Bode diagram. Valve characteristics are compared at the frequency of – 3 dB and at the phase of – 90°. The amplitude characteristic of the valve shows how fast the

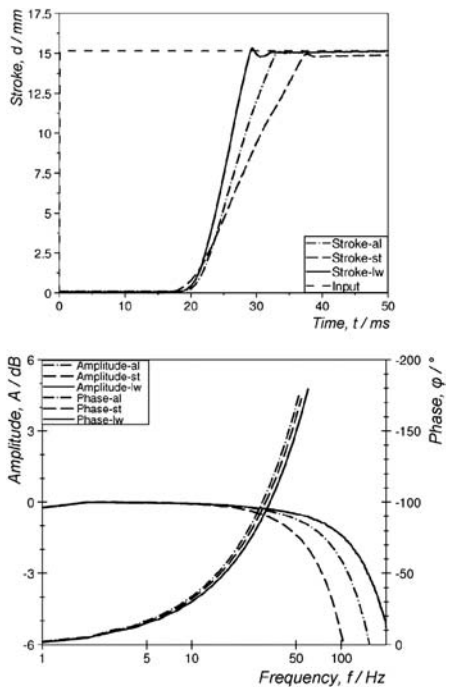

Figure 5: Influence of valve piston material on the valve dynamics
Slika 5: Vpliv materiala bata na dinamiko ventila

Table 2: Influence of valve piston material (mass) on valve dynamics
Tabela 2: Vpliv materiala (mase) ventilskega bata na dinamiko ventila

Material	Steel (st)	Aluminium (al)	Lightweight (lw)
Mass	140,9 g	59,4 g	39,6 g
Stroke + delay	38 ms	33 ms	29 ms
Stroke	21 ms	15 ms	12 ms
Delay	17 ms	18 ms	17 ms
Frequency 3 dB	74 Hz	110 Hz	151 Hz
Phase 90°	26 Hz	28 Hz	30 Hz

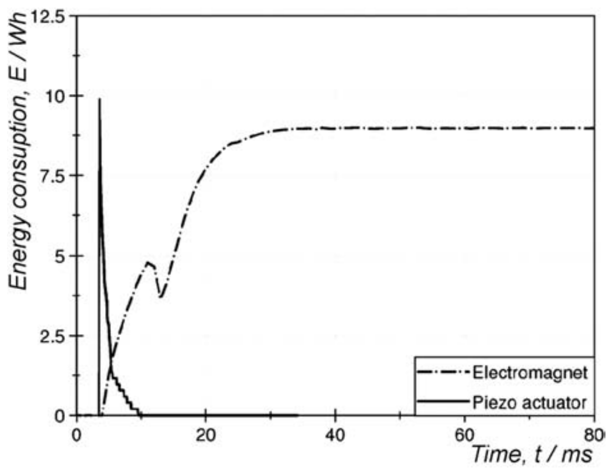

Figure 6: Energy consumption of piezoelectric and electromagnetic actuator at one switchover
Slika 6: Poraba električne energije s piezoelektričnim in elektromagnetnim aktuatorjem

Table 3: The analysis of the actuator electric energy consumption
Tabela 3: Analiza porabe električne energije aktuatorjev

Actuator	Energy consumption
Piezoelectric	$3{,}03 \cdot 10^{-6}$ Wh (one switch)
Electromagnetic	8,96 Wh

displacement of the valve piston is and the phase depends on the delay time between the input signal and the displacement (output signal). **Figure 5** and **Table 2** show the comparison of the dynamic characteristics of the valve with different piston materials. The input signal is a step function – start of supplying the actuator with electric energy. The response signal is a displacement of the valve piston. Aluminium (al), steel (st) and light-weight (lw) material pistons are implemented and their responses analyzed. The time delay of the displacement was for all pistons the same because of almost equal static friction between the valve piston and valve housing guidance. The difference is evident in the piston displacement time. The aluminium piston achieves 40 % shorter response time in comparison to the steel piston and the switchover time with the aluminium piston was thus 15 % shorter than with the steel piston. The light-weight material piston achieved even better results; the response time was 25 % shorter compared to the aluminium piston and switchover time was 14 % shorter. This proves how big the influence of the valve piston material on valve dynamics is.

Energy consumption of the piezoelectric and electromagnetic actuator was analyzed for one switchover, when the actuator stays under power for one hour (**Figure 6**). The results show that the energy consumption of the piezoelectric actuator is $3{,}03 \cdot 10^{-6}$ Wh and is $3 \cdot 10^{6}$ times smaller in comparison to the electromagnetic actuator which has a consumption of 8,96 Wh (**Table 3**). The energy consumption of the piezoelectric actuator is so small because it works on the same principle as a capacitor. Electric energy is consumed when the piezoelectric actuator moves to its maximum displacement position. When the piezoelectric actuator expands, there is almost no energy consumption – stationary state.

5 CONCLUSIONS

The paper is focused on the experimental analysis of the material and actuator influence on the dynamic and stationary characteristics of a pneumatic valve. In the research three different materials have been used for a valve piston: steel, aluminium and a light-weight material. The results of the experimental analysis show that a pneumatic valve with a light-weight material valve piston enables much faster moves - better short response time and the shortest switchover time which is essential for high dynamic automation systems. It is obvious, that the material (mass) of the valve piston has a big influence on the valve dynamics. The analysis of the energy consumption of the electromagnetic and the piezoelectric actuator shows a big advantage in lower energy consumption of piezoelectric actuator in the stationary state.

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