HYDRAULIC AND PNEUMATIC ACTUATING SYSTEMS WITH PIEZOELECTRIC ACTUATORS

Mihai Avram, Constantin Bucșan
Mechatronics and Precision Mechanics Department, "Politehnica" University of Bucharest

Abstract - The paper presents some aspects regarding the use of piezoelectric actuators for improving the performances of the hydraulic and pneumatic actuating systems. Some variants of proportional devices with piezoelectric actuators and mixed actuating systems are presented, along with the experimental models developed by the authors.

Keywords: pneumatic, hydraulic, actuator, piezoelectric.

1. Introduction

The performances of the hydraulic and pneumatic actuating systems can be improved using unconventional actuators in their structure, such as: piezoelectric, magnetostrictive, electro-chemical, shape memory alloy, electro-rheological, pneumatic muscle, etc. Such an actuator may be used to replace the classic actuators (the proportional electromagnet and the torsional motor) or to obtain mixed actuating systems in order to increase the positioning accuracy of these systems. Some aspects of this approach were presented in [1,2,3], other aspects are not yet solved.

The paper presents the contributions of the authors regarding the use of the piezoelectric actuators.

2. Piezoelectric actuators

A piezoelectric actuator is a very good option due to its remarkable performances, such as:
- theoretically unlimited resolution – under a nanometer;
- any variation of the supply voltage results in a linear continuous movement;
- very high actuating forces; heavy loads can be positioned with micrometer accuracy;
- under a millisecond response time; the elongation is limited only by the sound propagation speed through ceramic materials; accelerations thousands times bigger than the gravitational acceleration can be achieved;
- no moving parts, therefore no friction or clearances;
- the elongation of a piezoelectric actuator is based only on the deformation of a solid and there is no sign of ageing; the strength tests revealed no change after 500 million elongation cycles;
- very low power consumption; the piezoelectric effect converts directly the electric energy into linear movement.

This type of actuator is in fact a positioning element electrically controlled, working on the basis of the reverse piezoelectric effect (the dimensional change of a body when an electric voltage is applied). The PZT ceramic materials are produced in a great variety of types and they are the basic materials for piezoelectric actuators. Physik Instrumente produces low voltage PZT (the maximum applied voltage is 100 V) and high voltage PZT (the maximum applied voltage is 1000 V).

3. Proportional devices with piezoelectric actuators

The aim of the producers is to reduce the sizes of the pneumatic and hydraulic devices and to increase their performances. The researches of the authors follow these directions, trying to replace the classic actuators with piezoelectric actuators, in order to reduce the dimensions, to lower the hysteresis and thus to increase the performances of the devices, to simplify the electronic control circuits and thus to lower the cost of the equipment. The main problem to be resolved is to amplify the stroke of the piezoelectric actuator in order to match the displacement range needed for a proportional device. This range depends on the position of the actuator.

There are two cases to be considered:
- the actuator is implemented at the piloting level of the device;
- the actuator actuates directly upon the control element.

In the first case the actuator is used to control the output flow areas of a combined control half-bridges, usual of B+B type [4] (Fig. 1).

![Fig. 1 Piloting level actuating](image-url)
The piezoelectric actuator $A$ moves the flap $c$ against the nozzles $d_1$ and $d_2$, modifying the output arias $A_{e1}$ and $A_{e2}$ and thus the output pressures $P_{c1}$ and $P_{c2}$.

A pressure difference $\Delta P = P_{c1} - P_{c2}$ is obtained at the output of the system, which can be used to position the main slide valve of a proportional device (Fig. 2) and thus to control it. A movement of the flap in the range $[-0.15, +0.15]$ mm is needed and it has to be produced by the piezoelectric actuator $A$.

In the second case the maximum displacement of the actuator must be correlated with the nominal value of the flow-rate. For low and medium nominal flow-rates the maximum displacement of the control element must be in the range $0.6...0.8$ mm, depending on the system structure.

In both cases a piezoelectric actuator must be chosen in order to provide the maximum displacement. It is known that in the case of a stack type actuator the displacement of the free end is $1/1000$ of the stack height. Thus, a stack of about 800 mm is needed in order to obtain a displacement of 0.8 mm. This is unacceptable considering the aim of reducing the size of the actuator, so that the use of an amplifying system is necessary. A mechanical lever amplification or a hydraulic amplification may be used. Some variants of mechanical amplification are described in [4]. Fig. 3 shows the schemes of two such systems that became experimental models.

In the case of the system in Fig. 3,a the amplification is obtained using an articulated lever, but the size of the system along the lever is still relatively large. In the case of the system in Fig. 3,b an elastic beam is pre-strained between the body of the fluidic amplifier and a membrane. The piezoelectric stack pushes the membrane and the beam suffers a compressive buckling. The system is less sensitive to the hydrodynamic forces.

Fig. 4 shows a variant of hydraulic amplification of a piezoelectric stack displacement. The displacement of the piezoelectric actuator $l$ is amplified by a hydraulic amplifier consisting of the piston 2 and the plunger 3, and a working fluid between them [4]. Considering the volume $V$ is completely filled with the fluid and there is no leak, the displacement $x$ of the plunger is given by:

$$x = k_A \cdot x_A$$

where $x_A$ is the displacement of the actuator $A$, and $k_A$ is the amplification ratio, given by:

$$k_A = \left( \frac{D}{d} \right)^2$$

Fig. 5 shows two experimental models developed by the authors. The system in Fig. 5,a materializes the scheme from Fig. 3,b and the system in Fig. 5,b materializes the scheme from Fig. 4.
two proportional electromagnets (Fig. 6). The main stage of the distributor remained unchanged (Fig. 7).

Another option was the use of a piezoelectric actuator with internal mechanical amplification. The model P-287 from Physik Instrumente (Fig. 8) was chosen, having the following characteristics:
- supply voltage: $0..1000\,\text{V}$;
- displacement along $z$ axis without load: $700\,\mu\text{m}$;
- maximum pushing force along $z$ axis: $80\,\text{N}/10\,\text{N}$;
- resonance frequency without load: $380\,\text{Hz} \pm 20\%$;
- dimensions: $70\,\text{mm} \times 20\,\text{mm} \times 20\,\text{mm}$.

Another variant of proportional pneumatic distributor with two consumers [5] is shown in Fig. 10.

Fig. 11 shows the use of this distributor within a pneumatic system that rigorously controls the speed of the actuated load on both moving directions.

The system has the following components:
- the pneumatic linear motor $MP$;
- two one-way valves pneumatically controlled $SC_1$ and $SC_2$;
- the pneumatic proportional distributor shown in figure 10 $DPP$;
- the classic pneumatic distributor $DP$.

4. Mixed actuating systems

Fig. 12 shows a pneumatic positioning system having the following structure [9]:

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[Figures and diagrams as described in the text]
a pneumatic linear motor $MPL$;
- a position transducer $Tp$;
- a breaking device $DF$;
- a pneumatic proportional distributor $DPP$;
- a breaking pneumatic distributor $DPf$;
- a pressure regulator $RP$;
- an air supply $GP$.

The system can position the slide $m$ in any point of the working stroke with the imposed accuracy, which is limited by the working fluid. In order to increase the positioning accuracy a “piezoelectric module” (Fig. 13) was mounted on the slide $m$ of the linear pneumatic motor $MPL$ [10].

This module consists of two subassemblies:
- the fixed subassembly formed by the base plate 2, the “U” shaped piece 7 and the piezoelectric actuator with mechanical amplification 6;
- the mobile subassembly formed by the mobile plate 3 and the piece 8; the actuated load is placed on this subassembly.

The mobile subassembly is guided on four elastic beams 4. The actuator 6 acts upon the mobile subassembly by means of the balls 9 and 10 kept in contact with the pieces 7 and 8 and with the mobile part of the actuator 6 through the elasticity of the part “b” of the piece 7. The positioning is performed in two stages:
- a pneumatic positioning consisting in moving the slide $m$, the “piezoelectric module” and the actuated load 5 nearby the programmed position, meeting the condition: $y_p - \varepsilon_p \leq y_o \leq y_p + \varepsilon_p$, where $\varepsilon_p$ is the imposed error for the pneumatic positioning and $y_o$ is the position where the system stopped; in this position the breaking device is blocked (there control voltage $u$ is null);
- a piezoelectric precision positioning, consisting in moving the mobile part of the “piezoelectric module” by the piezoelectric actuator in order to obtain a final positioning error smaller than the imposed error $\varepsilon$.

A control algorithm was designed and a working program was developed in order to achieve the positioning.

5. Conclusions

The experimental models designed and built by the authors and the obtained experimental results showed that the two aims (reducing the sizes and improving the performances of the pneumatic and hydraulic devices) can be reached using piezoelectric actuators. Further theoretical and experimental researches are needed in order to optimize the built systems and to identify new variants of such systems.

6. References

[4] Avram M., Alexandrescu, N., Bucșan C., Utilizarea convertorilor piezoelctrici în construcţia echipamentelor hidraulice proporţionale, Construcţia de maşini, 2000 (52), nr.8, pag.8...10;
[6] Alexandrescu, N., Avram, M., Bucșan, C., Coman,