U.P.B. Sci. Bull., Series D, Vol. 73, Iss. 2, 2011 ISSN 1454-2358

MECHANICAL AMPLIFICATION SYSTEM FOR DISPLACEMENTS PRODUCED BY PIEZOELECTRIC ACTUATORS

Adrian Laurențiu CARTAL[1]

Lucrarea prezintă un concept de sistem de amplificare mecanică a deplasărilor produse de actuatori piezoelectrici în ideea folosiri acestui sistem pentru dezvoltarea unui echipament pneumatic proporțional de reglare şi control al debitului. Dat fiind faptul că, actuatorii piezoelectrici pot dezvolta forțe mari dar deplasări mici (de 5 până la 180μm) şi elementul mobil al echipamentului pneumatic necesită deplasări în jurul a 1-2 mm, este necesară asigurarea amplificării mişcării până la un nivel utilizabil în aplicațiile dorite. Lucrarea prezintă actuatorul utilizat, calculul şi proiectarea elementului de amplificare, rezultate experimentale obținute cu acesta.

This paper presents a concept of the mechanical amplification system of the displacement produced by the piezoelectric actuators in order to use this system for the development of proportional pneumatic equipment for controlling and regulating of the flow rate. Because, the piezoelectric actuators can develop large forces but small displacements (from 5 to 180 μm) and because the mobile element of the equipment needs displacements around 1-2 mm, it is necessary to assure an amplification of the displacements until a usable level in the applications mentioned above. The paper presents the used actuator, the calculation and the design of the amplification element and the experimental results.

Keywords: Piezoelectric actuator, mechanical amplifier.

1. Introduction

The need of actuators with precise, well-controllable displacement with a good force transmission in many applications focus attention on piezoelectric actuators, even though they came with a major drawback: small relative deformation (0.1 %) which results in a few micrometer displacements when voltage of 5 kV/cm along 33 direction is applied [1].

An improvement to the displacement performance with the same electric field and without losing force on the expense of extended device volume and materials costs can be made by stacking piezoelectric layers and metal electrodes [2].

[1] Engineer, Phd., Mechatronics and Precision Mechanics Department, Faculty of Mechanics and Mechatronics, University POLITEHNICA of Bucharest, Romania, email: adrian.cartal@upb.ro

Stacked piezoceramic actuators are compact, high-reliable and cost effective micro positioning components, and are specially designed for high-duty-cycle applications.

A piezoelectric actuator [3] produces extremely fine position variations by conversion of smallest changes in operating voltage. Force generation up to 100000 N, response times in the microsecond range and acceleration rates of more than 10000 g's can be obtained.

Fields of application are nano-positioning, high-load positioning, active vibration cancellation, precision engineering, chip manufacturing, optics, etc.

Stacked piezoceramic actuators consist of piezoceramic disks (0.2 to 1.0 mm thick), separated by thin metallic electrodes. Each individual layer is stacked and glued together with alternating poling directions respectively.

The displacement of a piezo stack can be estimated by

$$\Delta L \approx d_{33} \cdot U \cdot n \qquad (1)$$

where d_{33} = deformation coefficient (electrical field dependency; [4])

U = operating voltage

n = number of ceramic layers

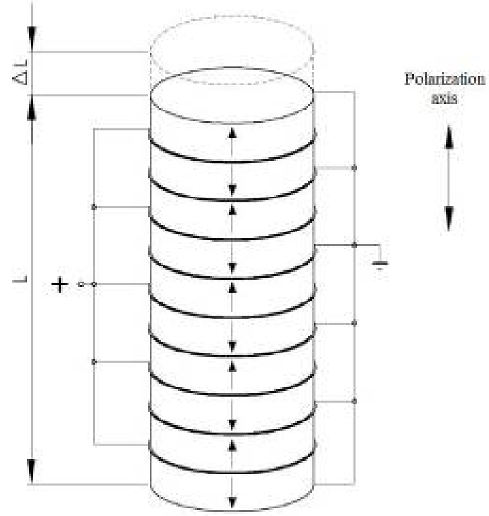


Fig. 1 A piezoelectric stack actuator.

The maximum electrical field which can be recommended for (reliable) operation is about 1 to 2 kV/mm (or 1000 V max. operating voltage). This actuator can be used for static and dynamic operation. Stack elements can withstand high pressure and exhibit the highest stiffness.

Piezoelectric stack actuators may be stressed in the axial direction only. The applied force must be centered very well. Tilting and shearing forces, which can also be induced by parallelism errors of the endplates, have to be avoided because they can damage the actuator. This can be accomplished by the use of ball tips, flexible tips, adequate guiding mechanisms etc.

In many applications, piezo actuators are used to produce displacements. If used in a restrain, they can be used to generate forces. A force generation is always coupled with a reduction in displacement. The maximum force (blocked force) a piezo actuator can generate depends on its stiffness and maximum displacement [5]. At maximum force generation, displacement drops to zero.

$$F_{max} \approx k_T \cdot \Delta L_0 \tag{2}$$

where:

ΔL_0 = max. nominal displacement without external force or restrain [m]

K_T = piezo actuator stiffness [N/m].

In actual applications the load stiffness can be larger or smaller than the actuator one. The effective force that a piezo actuator can generate in a yielding restraint is:

$$F_{max\_eff} \approx k_T \cdot \Delta L_0 \cdot \left(1 - \frac{k_T}{k_T + k_S}\right) \tag{3}$$

where:

ΔL_0 = max. nominal displacement without external force or restrain [m];

k_T = piezo actuator stiffness [N/m];

k_S = stiffness of external spring [N/m].

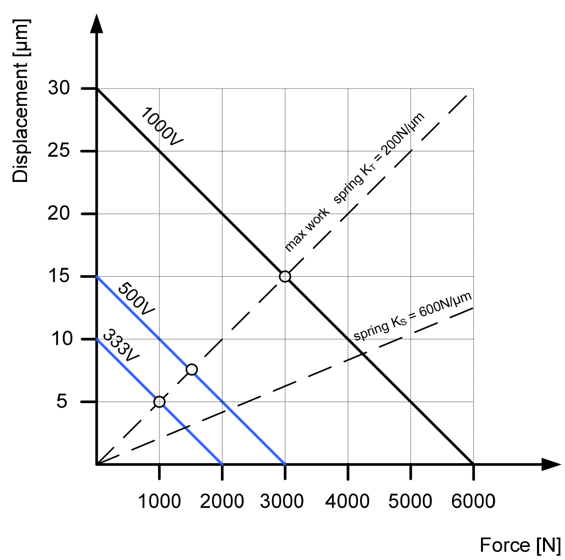


Fig. 2 Force generation vs. displacement of a piezo actuator (displacement 30 µm, stiffness 200 N/µm). Stiffness at various operating voltages [5].

The points where the dashed lines (external spring curves) intersect the piezo actuator force/displacement curves determine the force and displacement for a given setup with an external spring. The stiffer the external spring (flatter dashed line), the smaller the displacement and the greater the force generated by the actuator. Maximum work can be done when the stiffness of the piezo actuator and external spring are identical.

2. The chosen amplification solution. The calculation and design of the mechanical amplification system

Starting from an amplification subassembly with the leaf springs presented in [6], a similar amplification system was designed. The system should resist to forces developed by piezoelectric actuator presented in Table 1.

Table 1

Piezoceramic stack characteristics

Ordering Number	Displace-ment [µm 0±20%]	Diameter D [mm]	Length L [mm ±0.5]	Blocking force [N]	Stiffness [N/µm]	Capacitance [nF ±20%]	Resonant frequency [kHz]
P-010.20	30	10	30	2100	71	130	35

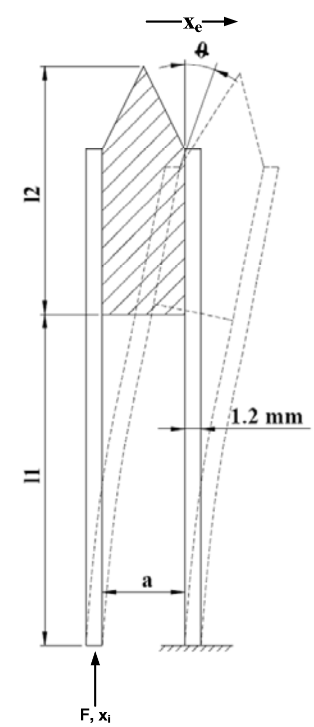


Fig. 3 The design principle of this amplification system

The system is described by the following equations:

$$x_e = \left(l_2 + \frac{l_1}{2}\right) \cdot x_i \cdot \left[1 + \frac{H^2}{3a^2} + \theta \cdot \frac{l_1}{2a} \cdot \varphi(\beta)\right] \cdot \frac{1}{a} \tag{4}$$

$$\varphi(\beta) = \frac{1}{16}\left[sh(2\beta) - \sin(2\beta)\right] + \frac{1}{4}\left[sh(\beta) - \sin(\beta)\right] + \\ + \frac{1}{8}\left\{\frac{(1+\cos\beta)^2}{\sin^2\beta}\left[1 - \frac{\sin^2\beta}{2\beta}\right] + \frac{(1+ch\beta)^2}{sh^2\beta}\left[1 - \frac{sh^2\beta}{2\beta}\right]\right\} \tag{5}$$

$$\beta = \sqrt{\frac{F \cdot l_1^2}{E \cdot I}} \quad \text{and} \quad I = B\frac{H^3}{12} \tag{6}$$

where:
l_1 = leaf springs length;
l_2 = rigid part length;
F = longitudinal effort in the spring;
E = Young's modulus for the spring material;
I = moment of inertia of the spring cross section;
H = spring thickness;
B = spring width;

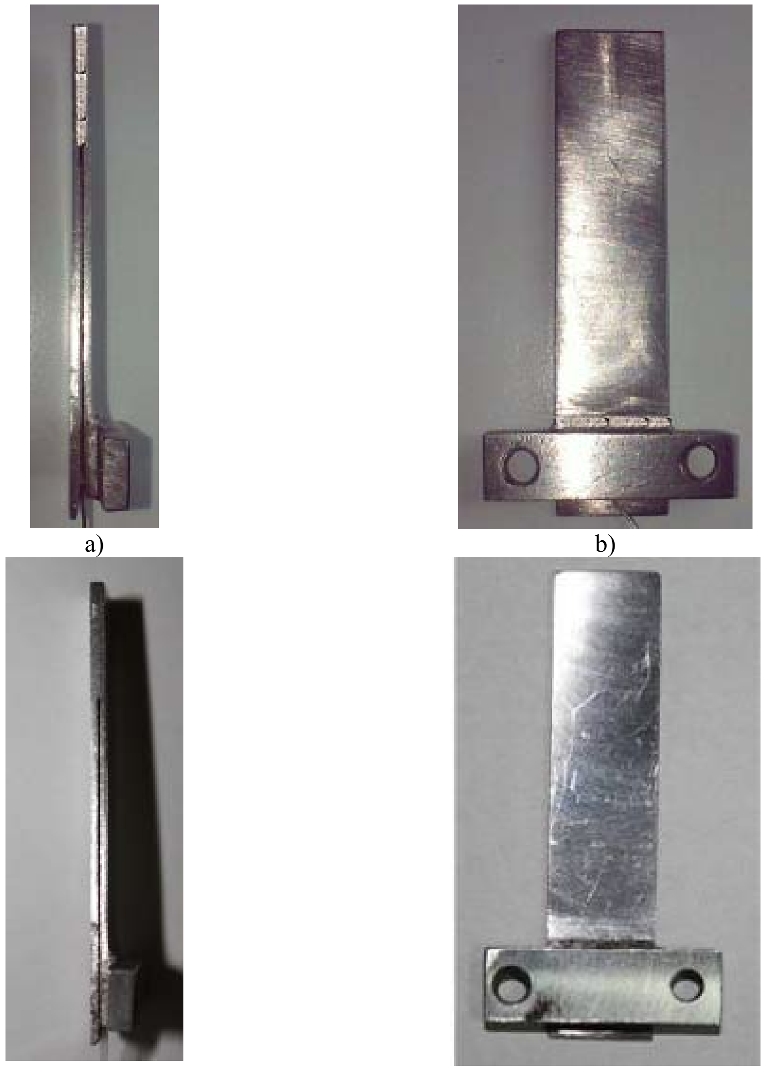
$\theta = \frac{x_i}{a}$

a = distance between leaf springs.
Equation (4) can be approximated to:

$$x_e \cong \frac{2l_2 + l_1}{2a} \cdot x_i \tag{7}$$

There is no theoretical error if the complete relation is used (4). The error appears when the approximate relation (7) is used and it is given by the difference between the two expressions. The danger of buckling of the leaf springs appears due to the increas of the necessary axial effort with the sensibility. The maximum multiplication ratio is around 200.

Considering a needed displacement of x_i = 30μm and aiming an amplification of 10 times, the spring was dimensioned with the support of the above relations. Matlab software was used.



a) b) c) d)

Fig. 4 The developed amplification system: manufactured by laser welding (a, b) and manufactured with a wire on a spark erosion machine (c, d).

In order to make calculations easy, for the initial dimensioning, the approximate equation (7) was used. The obtained values were rounded up and reintroduced in the program, but this time the complete relation was used. The obtained values were: a = 1mm; l_1 = 34mm; l_2 = 13mm; B= 12 mm; H = 1.55mm. As material, it is chosen hard steel with the Young's modulus E = 210000 N/mm^2. With these values the theoretical amplification resulted from (4) is of 11.7.

A first amplification system was manufactured by laser welding of three leaf slides, two of 1.55mm and one of 1mm width in order to make them rigid. In order to be able to fix the leaf springs on the experimental setup, they were welded to a supporting part [7]. The result is presented in fig. 4 a, b. In order to be closer to the resulted dimensions from the computing program, the second amplification system was made from a steel semi-product, machine-made in the desired form, in order to be cut with a wire on a spark erosion machine (fig. 4 c, d).

3. The experimental results

In order to be able to verify the values obtained theoretically in the previous chapter, an experimental setup was designed. The setup was used for the test of the amplification system, its behavior, as to measure the input and output displacement of the system.

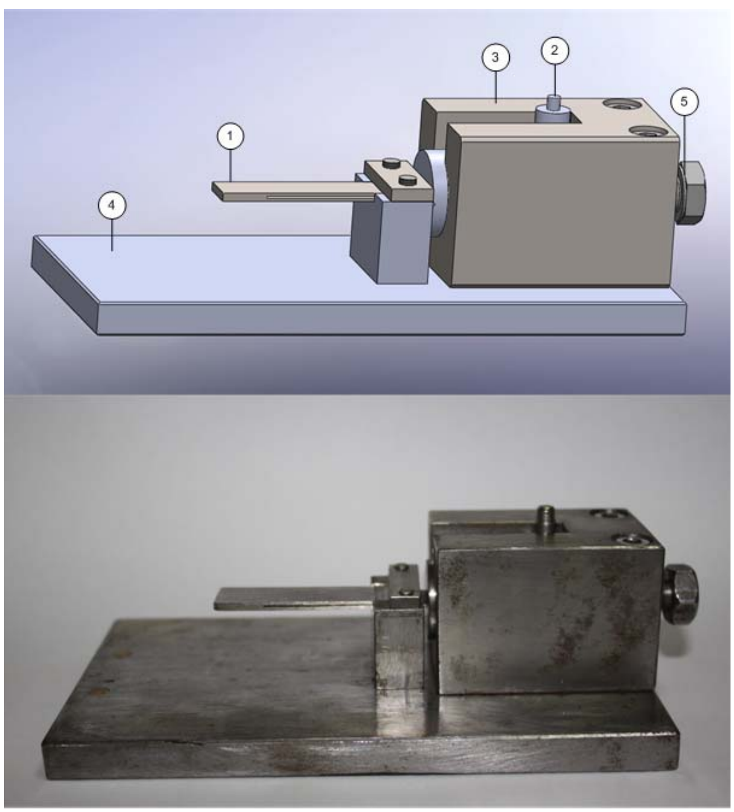


Figure 5 Experimental assembly

The experimental setup is composed of amplification system 1 which is fixed on the mounting plate 4, housing 3 of the force transducer 2. The screw 5 is used for the displacement of the amplification system. The screw 5 has a special pitch of 0.75mm in order to move the leaf spring with a linear increment as small as possible. For establishing the displacement of the leaf spring given by the screw, on the screw head and on the leaf spring output, two inductive measuring probes with 1 µm resolution (MAHR Militron 1202D) were placed, as it can be seen in Fig. 6. The experiments took place in a room with controlled temperature and humidity, on a measuring table „Standa Opto-Mechanis". This measuring table met high rigidity standards, flatness of the working area and vibration isolation. The mounting plate 4 was fixed by the help of two screws and of 2 clamps on the measuring table.

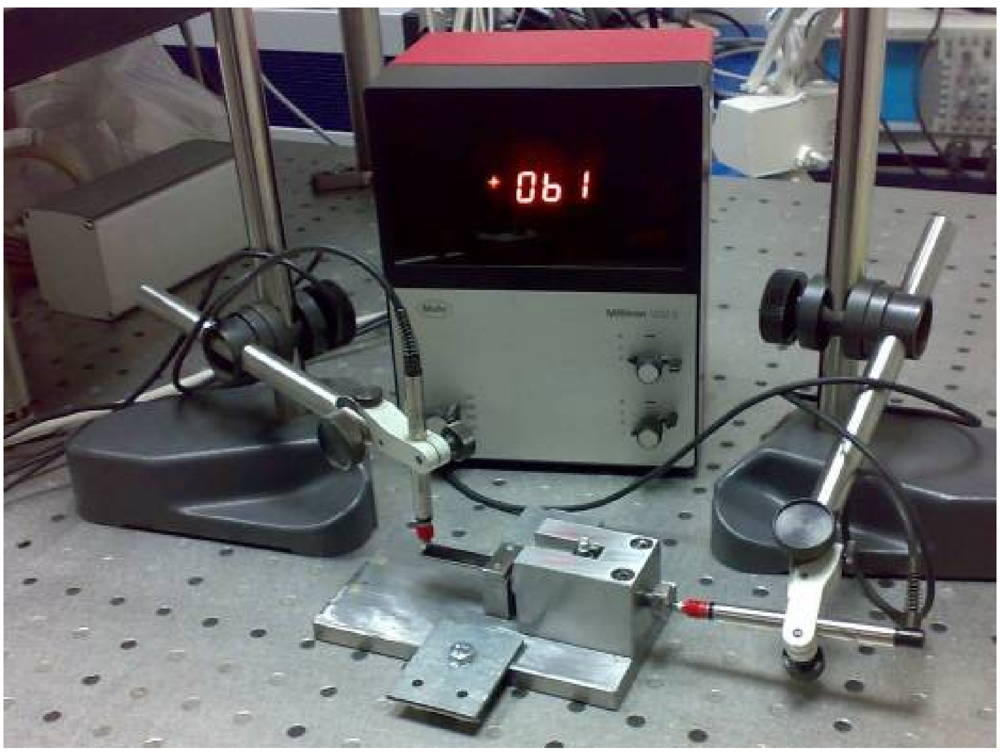


Fig. 6

The first leaf spring subjected to tests was manufactured by laser welding. The data given by the two measuring probes were acquired, then computed and displayed in the graph presented in Fig. 7.

The resulted average amplification was of 8.33 towards theoretical amplification which was of 10. The difference could appear due to the fact that the leaf springs were welded only on the external side, because the internal surfaces were impossible to be reached for welding. The second reason could be that by welding the amplifying mechanism on the supporting element, the length of the elastic part of the leaf spring l_2 was downsized. After several measurements, a crack on one of the welds done between the support element and the leaf spring was noticed. Therefore as it is showed in the amplification characteristic (fig. 7), the leaf, does not slide back to its original position.

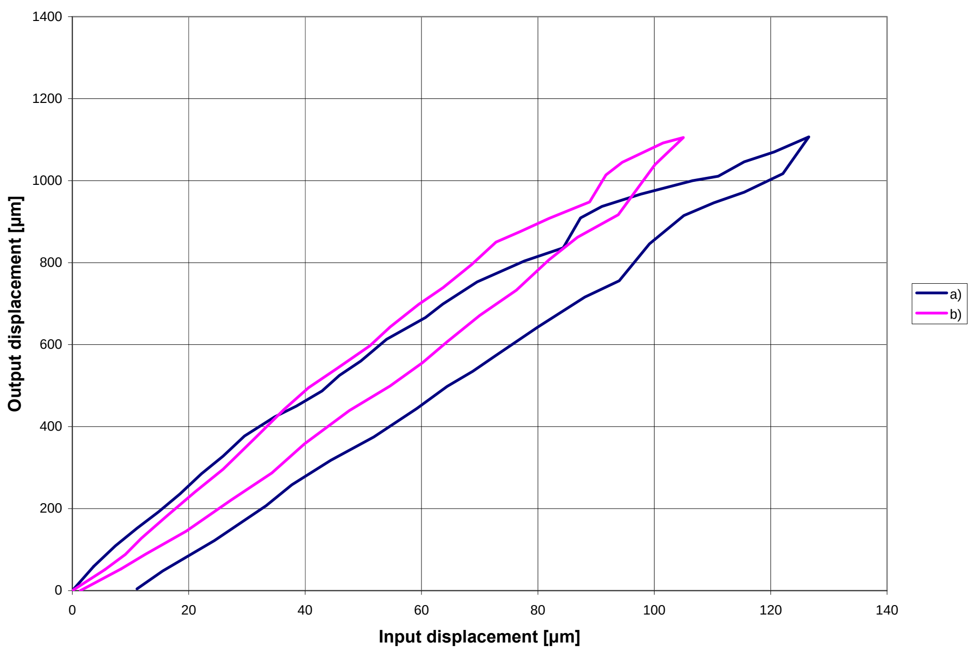


Figure 7 Amplification characteristic for: a) welded leaf spring and b) cut leaf spring.

Due to this, the decision to make the leaf spring from a steel semi-product cut with a wire on a spark erosion machine was made. The diameter of the wire is 0.5 mm, and the cut left behind has the width of 0.6mm. With these data being introduced in the calculation program mentioned in the previous chapter (a=0.6mm, H=1mm and l_1, l_2, B from chapter 2), the theoretical amplification of this leaf spring is 10.5.

6. Conclusions

Mechanical amplification structures were designed and accomplished to enhance the displacements of pre-stressed piezoceramic stacks. Due to properties of the pre-stressed piezo actuators (small displacement, moderate load capacity and small size) simple mechanical amplifiers are enough to produce displacements over millimeter with piezo actuation. Yet these mechanisms are easily implemented and manufactured for several precision engineering applications.

The resulted amplification structure, inspired by a measurement subassembly, has an amplification of approximately 10 times the displacement from the mechanism input, at the low overall dimensions. In order to be able to use the displacement given by the piezoelectric stack, a lever of first grade with a 4 times amplification of the input displacement was also used, but this is not a part of the present paper. Total amplification of the system is of 10 x 4 = 40 times. Having a displacement of 30 μm given by the piezoelectric stack, the obtained displacement at the output of the system is 1.2 mm. This displacement can be used to drive a mobile element of a flow adjustment and control equipment - the purpose of the research.

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