# 420. Empyrical model of layered piezoactuators

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**Abstract.** Complex piezomaterials are frequently used in various mechanical systems. The piezomaterial, used in layered piezoactuators requiring high precision displacements, has indicated that accuracy depends on their design and technological factors.. The bifurcation problem of layered piezoactuator has been solved by evaluating physical properties of piezoelements and sealing material. That created posibility to prove that layered piezoactuators have a lot of possibilities of static operation. The original solution of layered piezoactuators enabled the choice of optimal initial stresses in piezostacks. Empyrical model of layered piezoactuators has revealed possibilities to optimize design of various mechanical systems.

**Keywords:** layered piezoactuators, displacement, binder material

## Introduction

One of the essential requirements for layered piezoactuators is their capability to transfer unipolar or bipolar forces. In the first case, a piezostack acting in one direction is made of separate piezoelements and special binding materials. They operate in a mode of their positive deformation (elongation due to neutral position) when the applied voltage is positive inspect to polarization. A piezostac returns to its initial position under negative deformation (contraction) when voltage of opposite sign is applied to binding materials. Mechanisms of this type are frequently used in adaptive optics and various mechanical systems. The second case ensures the possibility of displacements in opposite directions from the neutral position – bipolar force. That happens when a piezostac elongates from the initial position under the positive deformation while the deformation to the opposite direction occurs as a result of the elastic strain. Layered piezoactuator with a piezostack is superior over those with a single-layer because summing up. Deformations of each element, the displacement of a layered piezoactuator can be increased. Their mechanical properties are also significantly augmented. Therefore, dynamic characteristics of each individual element of a layered piezoactuator have to be determined separately. Layered piezoactuator piezoelements with similar characteristics have to be selected for assembling of layered piezoactuators. The input electrical energy is larger than the output mechanical energy, when piezoceramics are deformed by external electric field. The ineffective electrical energy is stored as electrostatic energy in the piezoconverter and reverts to the power supply in the final stage of an operating cycle, because displacement of a layred piezoactuator can be increased by summing up deformations of each elements composing a dynamic model [1,2]. It consists of concentraded masses $M$ and k - interelement packings. For selection of constructional and technological parameters the algorithm of dynamic characterisitcs has been set up constructional and technological parameters. Parameters of internal deformations have been also evaluated. The common equation of an axial piezostack motion is:

$$[M]\{\overline{\overline{X}}\}+[H]\{\overline{X}\}+[C]\{X\}+\{F(X,\overline{X})\}=\{F_b(t)\}+\{P_H\} \qquad (1)$$

where $\{X\},\{\overline{X}\},\{\overline{\overline{X}}\}$ - vectors of displacements, mass and accelerations, respectively; $[M],[N],[C]$ - matrices of mass, shock-absorption, elasticity, respectively; $\{F(X,\overline{X})\}$ - vector of nonliner forces; $\{F_b(t)\}$- vector of internal deformations due to electric voltage; $\{P_H\}$ - vector of loading force. Theoretical investigation of piezostacks and dynamic analysis of their components have indicated that an increase in the loading force and initial tension decrease harmonic components of oscillation. Natural frequencies of piezostack decrease sharply with an increase of number of piezoelements. Mechanical and electrical laws pertaining in combined stack are analysed separately and their interelation is written by a mathematical expression.

$$\overline{\sigma} = \left[c^{E}\right]\overline{\varepsilon} - [e]\overline{E} \text{ and } \overline{D} = [e]^{T}\,\overline{\varepsilon} + \left[\text{э}^{s}\right]\overline{E} \qquad (2)$$

Where $\sigma$ - mechanical stress; $D$ – vector of electric displacement; [ $c^{E}$ ] – stiffness tensor; [ $e$ ] – tensor of piezoelectric constant; [ $\text{э}^{S}$ ] – tensor of dielectric constant. Stiffness matrix $[K_0]$ is expressed by

$$[K_0] = \int_{V^e} [B]^{T}\left[C^{E}\right][B]\,dV \qquad (3)$$

where matrix $[B]$ is bound by deformations and displacements $\overline{\varepsilon} = [B]\overline{\sigma}^{e}$ , and matrix $[B]^{T}$ is transformation matrix $[B]$

$$\int_{V^e} d[B_L]^{T}\{\sigma\}dV = [K_\sigma]d\{\delta\} \qquad (4)$$

where $[B_L]^{T}$ - transformation matrix $[B_L]$ estimating nonlinearity of deformations, matrix $[K_\sigma]$ estimates piezoelectric properties described by formulas (2). Coefficient of proportionality $\lambda$ indicates the extent of the load increase in order to obtain critical strength [ $\delta$ ]. The critical load – $P_{kp} = P\,\lambda$ .

Values of critical loads are obtained for piezostacks a) with disk elements $P_{kp}$ = 280244.48 $N$, b) with ring elements $P_{kp}$ = 269455.07 $N$.

## Experimental Analysis of Layered Piezostacks

Piezostacks used in mechanisms requiring displacements of high precision have indicated that accuracy depends on their design and technological factors. Layered piezoactyators can be bimorph, axial and combined stacks (Fig. 1).

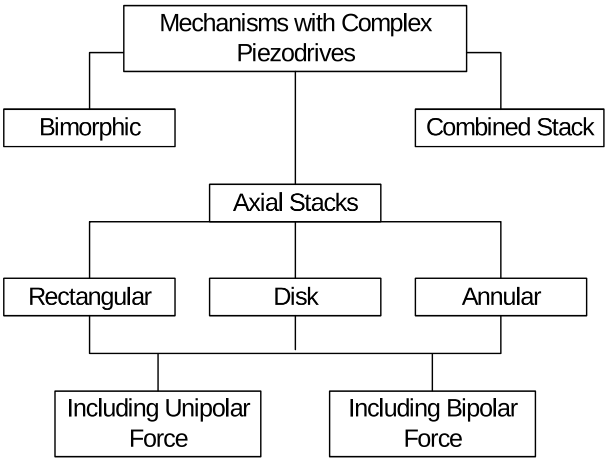

**Fig. 1.** Diagram of bimorph, axial and combined piezostacks

Experimental invesigation enables conclude that the electromechanical feedback affects correction of the hysteresis loop of piezostacks [3,4]. It is evident that the hysteresis loop can be corrected up to 0.2% of the maximum displacement by applying the electromechanical feedback. Piezostack is arranged along one axis which is perpendicular to that of the displacement. Due to the symmetrically set lever mechanism, all forces emerging separately in each diamond-shaped part add up into one uniformly acting force whose direction coincides with that of displacement. In this way, the superfluous bending moments usually emerging in asymmetric systems are precluded and the displacement accuracy is increased. In order to determine more precisely the initial stress values in piezostack and to choose the optimal version in the piezoconverter design, a few piezoelements are inserted to the sensor. They significantly improve the operation parameters of the piezostack increasing in accuracy and releability.

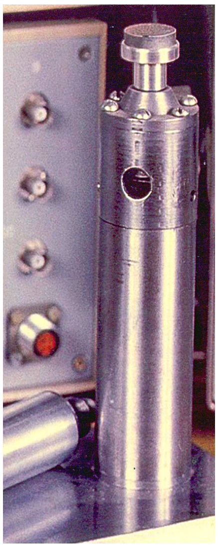

**Fig. 2.** Layered piezostack

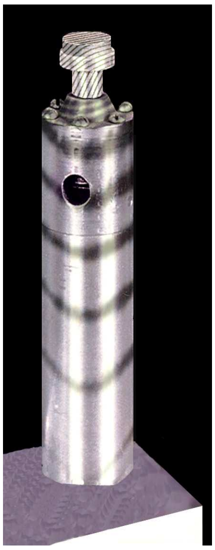

**Fig. 3.** Holographic interferograms

The experimental investigation of layered piezostack (or their separate elements) by means of holographic interferometry enables one to obtain appreciably larger amounts of information about the surface deformation in comparison to traditional methods [5]. Fig. 3 shows an interferogram when a control signal is sent only to one active control piezostack of layered piezoactuator.

According to the calculations the piezostack of constituent elements tied together by binding material is a system having great static strength . Therefore these systems are used in mechanisms operating under heavy loads and requiring very precise displacements Upon having analysed a stack made of piezomaterial, the authors have estimated that amplitude frequency characteristic (AFCh) of the piezostack depends on temperature range. To maintain the same operational properties of a piezostack. Research has been carried out with the aim to find out conditions ensuring the stability of a mechanism. Then the conclusion has been made that the main displacement is performed by the bottom part of the piezostack, while he upper part (approximately 1/3 of its height) develops deformations of negligible usefulness. In addition to the investigation results shown in Fig. 4, this fact admonishes that precaution should be taken when choosing the number of piezoelements for obtaining the higher displacement amplitude. The desired value of displacement can be achieved with lower power and labour expenditure then the optimal number of piezoelements is selected and manufacturing conditions which do not restrict the displacement value but restrict the deflection of piezostack from the vertical axis are observed. Loading characteristics of piezostacks have been analyzed by changing the supply voltage from ± 100V to ± 400V, Fig. 5. This graph reveals the dependence of a piezostack having initial tension: increasing the tension force without any initial tension the piezostacks disintegrate, while the value of displacement in a piezostack with initial tension decreases very slightly. It is the point of great importance in adaptive optics devices where piezostacks can be fastened only at one end, while the free end of element can bend to both sides from the state of equilibrium when loaded up to 500 N.

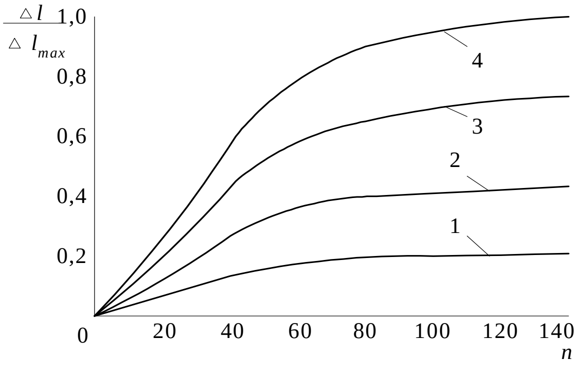

**Fig. 4.** The number of piezoelements when 1 - U=100V, 2 - U=200V, 3 - U=300V, 4 - U=400V

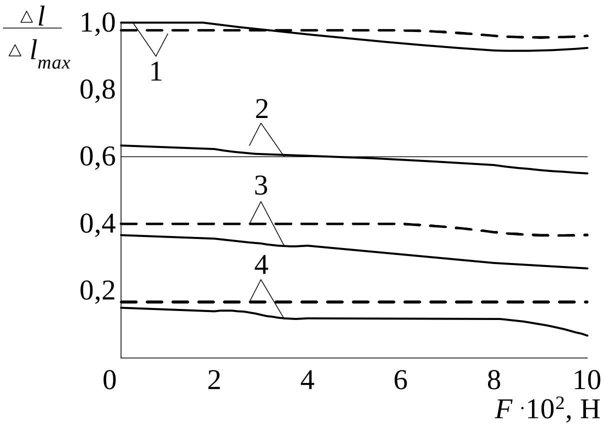

**Fig. 5.** Dependnce of piezostack displacement on the loading force: 1- U= +100V; 2 -U= +200V; 3 - U= +300V; 4 - U= +400V

Curve 1 (Fig.6) represents AFCh of a piezostack under natural climatic conditions. Curves 2 – 7 – AFCh at the temperature of – $50^0$ C. Experiments were made in the temperature range of $\pm 50^0$ C. The piezostack was examined for 1.5 h and AFCh was recorded every half hour. Fig. 7 represents 3 curves in the following time intervals : 1 – 0.5 h; 2 – 1 h; 3 – 1.5 h .

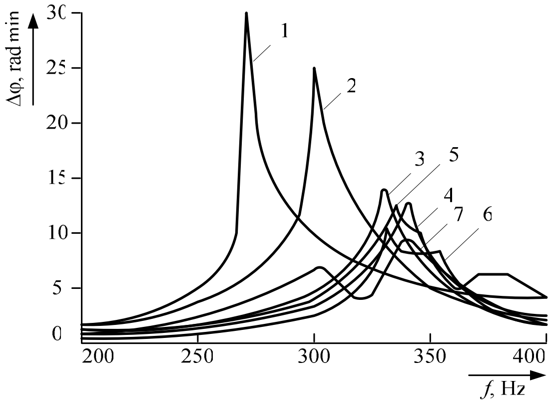

**Fig. 6.** Curve 1- AFCh under natural climatic conditions 2–7 – AFCh when temperature: – $50^0$ C

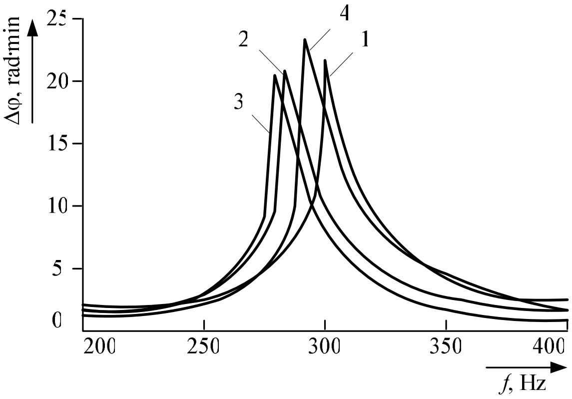

**Fig. 7.** Experiments when the temperature range off $\pm 50^0$ C

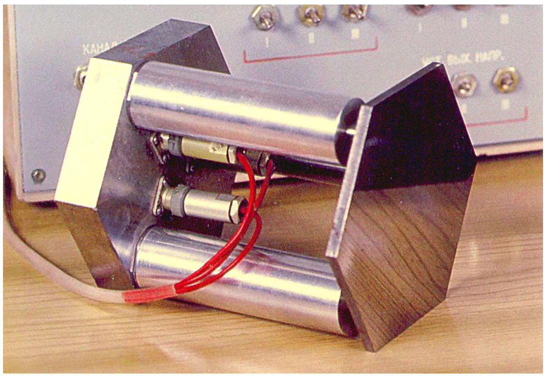

**Fig. 8.** Piezostacks application in optical ystems (with three stacks)

In order to obtain the maximum displacements in layered piezoactuators the material and diameter for a pin (Fig.10) has to be properly chosen as both of them effect the initial stress. Choice of the initial stress enables to determine exactly an operation range for the piezostack to meet functional requirements for the precise displacement mechanisms. The initial strain force of the pin made of 2mm diameter beryllium bronze which ties together the piezopacke is 1500 N. The initial supply voltage is $\pm 400$V. It is evident that in order to increase the frequency range of the piezostacks when its amplitude is minimum, a generation and inspection should be performed by means of a signal generator.

In figure 8 illustrates the dependence of piezostack displacement on the value of initial stress for various diameters and materials of the pin. Fig. 9 presents the dependence of piezoelement displacement on the initial tension force and curves 1, 2, 3 are obtained by applying tension forces 20N, 150N, 200N respectively. The analyzed criteria have made it possible to choose the piezostacks of an optimal construction having a maximum displacement assembled of ПКР-7М with the binding material ЭД-20 and a beryllium bronze pin of 2mm diameter.

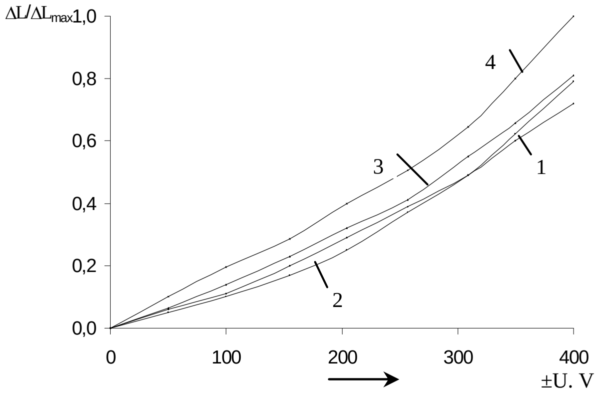

**Fig. 9.** Dependence of displacement values on supply voltage with different materials of pin : 1- 30G, 2 - 65G, 3 - OT4, 4 - bronze

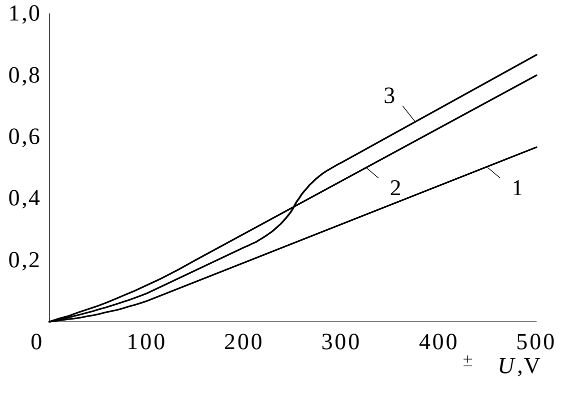

**Fig. 10.** Dependence of piezoelement displacement on the voltage under different initial force values: 1- 20N, 2 - 150N, 3 - -200N

In Fig. 10 the curves show the piezostacks displacements when using piezoelements of different ceramics. Piezostacks banding Fig. 9 technologies have been also examined. Piezostaks have been made of different materials however, their manufacturing technology was absolutely identical. In order to get the greatest displacement in a piezostacks size of the pin and its material have to be taken into account. Increasing of tension force without any initial tension disintegrate piezostacks, while the value of displacement in a piezopacket with initial tension decreases very slightly.

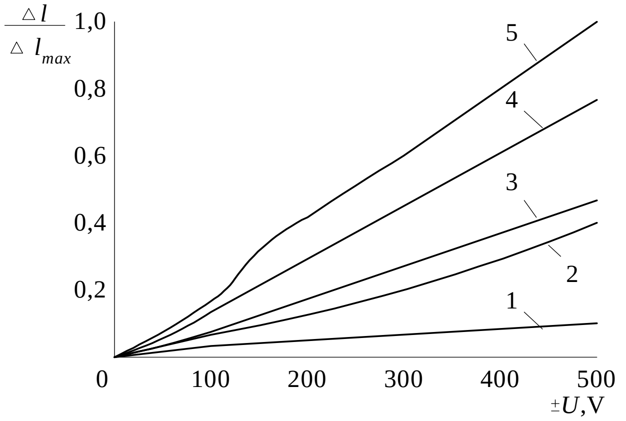

**Fig.11.** Dependency of piezostack displacement on the supply voltage using different ceramics:1-ПКП16; 2 - ПКР22; 3 - ЦТС19; 4 -ПКР12; 5 - ПКР7М

Dynamic characteristics of mechanisms containing piezostacks, defined under different temperature conditions, have indicated their operational potentials in temperature range from $\pm 200^0$C iki $\pm 50^0$C, and also under thermal impact. Applying of the above mentioned piezopacket properties and selecting materials for the other parts help in obtaining mechanisms possess proper technical and operational characteristics. Dependence of basic piezostaks parameters on temperature changes

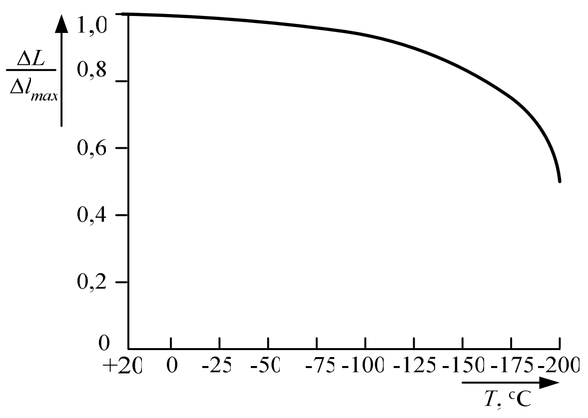

**Fig. 12.** Dependence of piezostack displacement on temperature ($\pm 20^0 C, \pm 200^0 C$)

showed the change of piezopacket quality. This affects the amplitude of vibrations displacement and stability of resonance frequency. Therefore, strenght of materials and temperature changes have to be taken into consideration designing a mechanism which contains piezostacks. This conclusion can be drawn from curve Fig.11 which shows dependence of piezostack displacement on temperature ($\pm 20^0 C, \pm 200^0 C$).

## Conclusions

Dynamic characteristics of each individual element of layered piezoactuators have to be determined separately. Piezoelements with similar characteristics have to be selected for assembla of piezostacks. The bifurcation problem of a layered piezoactuators has been solved by evaluating physical properties of piezostacks piezoelements and sealing material. The original solution of the mechatronic system enabled the choice of optimal initial stresses in layer piezostacks. The experimental investigation of layered piezoactuators with pezostacs have revealed possibilities to optimize their design and materials for optaining maximum displacements. Holographic interferometry method used in the experimental work has proved solutions of differential equations and used for describing conclusions of the investigation. Applying of the above mentioned piezostacs properties and selecting materials for other parts allows dwsigning of mechanisms, characterised by proper technical add operational properties. Layered piezoactuators are used for ensuring precise and stable positioning of mechanisms used in mechanical, optical systems and medical equiment.

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