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Simulation and measurement of stroke in piezoceramic combs with a decrease in cross-sectional area of control elements

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Numerical modeling of multilayer piezoactuators with a cross-sectional area of 2×2 mm was carried out. It was shown that when interdigitated switching is used in piezoactuators, a local redistribution of transverse strain maxima is observed, which leads to a decrease in the mechanical strength and reliability of control elements. Piezoceramic combs with identical linear dimensions were produced and the mechanical and electrical properties of the developed elements were measured. It was revealed that stroke at a control voltage of 300 V decreases from 4 to $1.5\,\mu$m when using the interdigitated switching method in comparison with multilayer actuators of larger cross-section due to a decrease in the effective polarization area of piezoactuators. Piezoceramic combs with wire commutation were manufactured, where the displacement at a control voltage of 300 V was $4.6-4.8\,\mu$m.

Keywords: wavefront correctors, multilayer piezoactuators, finite element method, adaptive optics.

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1. Introduction

Piezoceramic elements, due to their unique properties, are widely used in many scientific and applied fields, as they are capable of converting mechanical stress into electrical energy (signal detection [1], energy harvesting [2]) and vice versa (actuation [3]). The latter is called the inverse piezoelectric effect, the key point of which is to change the linear dimensions of a component under the influence of a control voltage. This phenomenon has found its application in various fields: active optics (scanners, motorized platforms, etc.) [4], stepper motors [5,6], mass flow controllers [{] 7}. A special place in this series is devoted to adaptive optics [8–12]. The high popularity of using piezoceramic multilayer stacks as control elements for wavefront correctors is largely dictated by their reliability, high blocking force and sensitivity to applied voltages [13]. However, when creating electronic, including optoelectronic, devices based on piezoceramic materials, there is a tendency to create miniature, multifunctional and energy-efficient components, which imposes certain restrictions on the use of such elements [14]. In addition, the development of such devices is associated with the need to evaluate their mechanical and electrical properties with high accuracy [15]. Therefore, recently methods of mathematical modeling based on the finite element method have become actively widespread [16].

2. Modeling of piezoceramic rulers with cross-sectional area 2×2 mm

When creating deformable mirrors of the piezoactuator type [17–20] with high spatial resolution of control elements, there is a problem of creating reliable multilayer actuators. Moreover, such elements should generate a significant amplitude of movement. Theoretical and experimental studies were carried out to analyze the opportunity of reducing the area of the actuators and at the same time ensuring the reliability of the design.

To perform the theoretical experiment, the ANSYS mathematical modeling software environment was chosen due to the availability of modern solvers of computational problems with high-dimensional sparse matrices, which makes this software package indispensable from the point of view of carrying out research and design work in the field of piezoelectric instrumentation.

In this software system, a comparative analysis was carried out to describe the structure of a multilayer piezo actuator during the transition from an area of $16\,\text{mm}^2$ (4×4 mm) to $4\,\text{mm}^2$ (2×2 mm). Piezoceramic material PKP-12 was used to study the mechanical properties. The electrical properties of this material are presented in [21].

When analyzing by the finite element method, it was revealed that the absolute deformation of multilayer actuators along the applied stress is equal to $5.33\,\mu$m for an element with an area of $16\,\text{mm}^2$ and $5.52\,\mu$m for an element with an area of $4\,\text{mm}^2$ (Fig. 1). These values correspond to

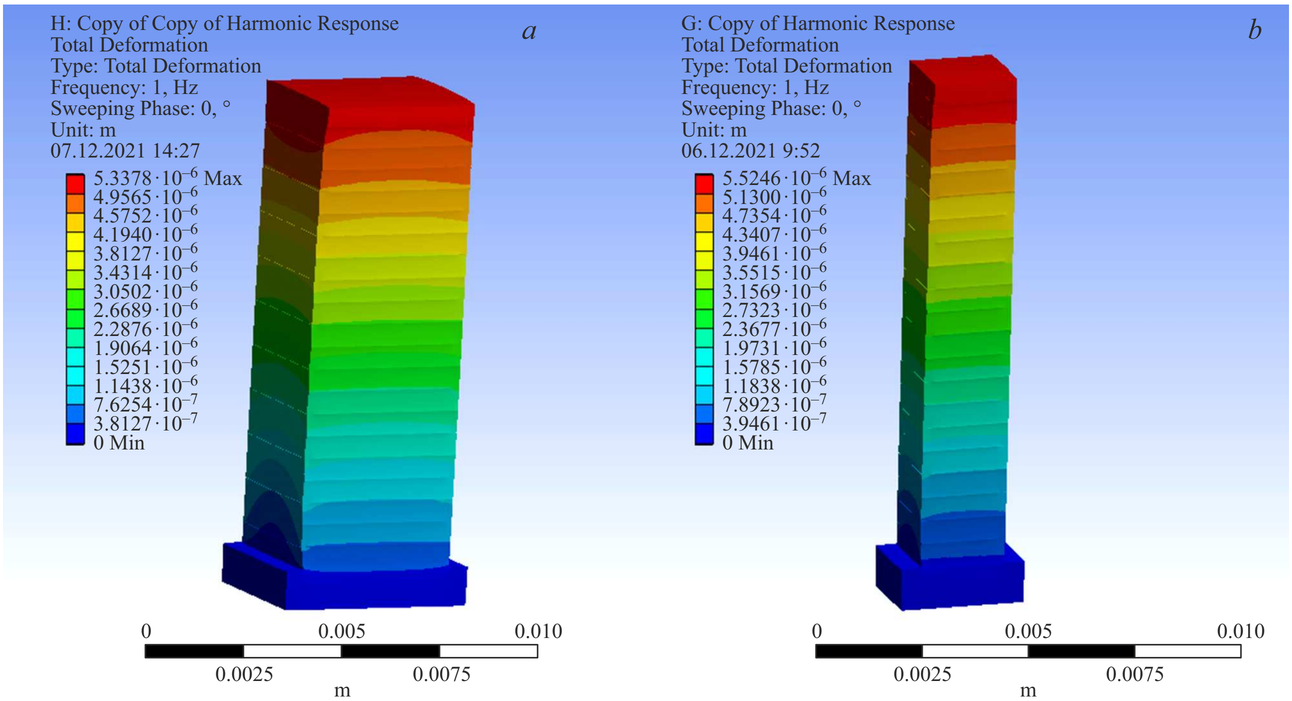

Figure 1. Absolute deformation of multilayer actuators with 20 active layers with an area of 16 mm^2 (*a*) and 4 mm^2 (*b*) along the application of a voltage of 300 V.

conditions in which all layers of the actuator are completely mechanically coordinated with each other.

In this model, an interdigitated technique was used for switching piezoceramic layers, when the active layers are electrically connected in parallel on even and odd layers. The area not covered with a silver film of thickness 200 μm acts as an insulating region. Thus, the active area of the layer is reduced by 0.8 mm^2 in the first case and by 0.4 mm^2 in the second; accordingly, the effective polarization area is reduced to 14.4 mm^2 in the first case and to 3.2 mm^2 in the second. As a result, along with the appearance of local areas of tension, there is a decrease in the strength characteristics of the actuators. This effect is clearly shown in Fig. 2. During the simulation, it was shown that in the case of an actuator working area of 14.4 mm^2, there is a „barrel " effect on the transverse deformation, which indicates that the assembly operates as a single whole. Accordingly, such an actuator can be reviewed as a monolithic object. With a working area of 3.2 mm^2 , there is a local distribution of maxima of transverse deformation, which leads to a decrease in mechanical strength and, accordingly, to a decrease in the reliability of the entire system.

This fact was also confirmed by the results of layer-by-layer pressure modeling (Fig. 3). With an area of 14.4 mm^2, the maximum pressure is distributed over the entire area of the piezoelectric layer, which is not with a cross-sectional area of 3.2 mm^2, where the pressure is concentrated at the edges of the piezoelectric layers (Fig. 3, *b*).

It was shown that the creation of actuator lines with a smaller cross-sectional area leads to the emergence of local pressure concentrations at the edges of the elements and does not allow the use of such elements as control elements in deformable piezo-actuator-type mirrors.

There are various modifications for creating electrical switching of multilayer actuators: interdigitated, in-slit, with a floating electrode and wire [22]. From the point of view of creating large batches of multilayer actuators, the most commonly used method is interdigitated switching due to the simplicity of this method. To test the model experiment, which showed the occurrence of local pressure concentrations at the edges of the elements, lines of actuators with an interdigitated switching type were manufactured.

The dimensions of the actuator were close to those used in the modeling and amounted to 4 × 4 mm (surface area 16 mm^2) and 2.5 × 2 mm (surface area 5 mm^2). The size of 2.5 × 2 mm is determined by the technological limit of the equipment used in the manufacture of this type of actuator.

Reducing the cross-sectional area of the actuator in the line from 16 mm^2 (4 × 4 mm) to 5 mm^2 (2.5 × 2 mm) led to a decrease in the movement of an individual actuator from 4 μm to 1.5 μm at a voltage of 300 V. This is due to a decrease in the effective cross-section of the actuator layer and lateral clamping of the package due to heterogeneous deformation on each plate of the package (Fig. 4). The use of the entire area of the active layers of piezoceramics can be achieved by changing the switching method. This method, despite the relative high cost in comparison with the interelectrode switching method and the labor-intensive process, allows to increase the uniformity of distribution of mechanical loads inside the actuator and increase the

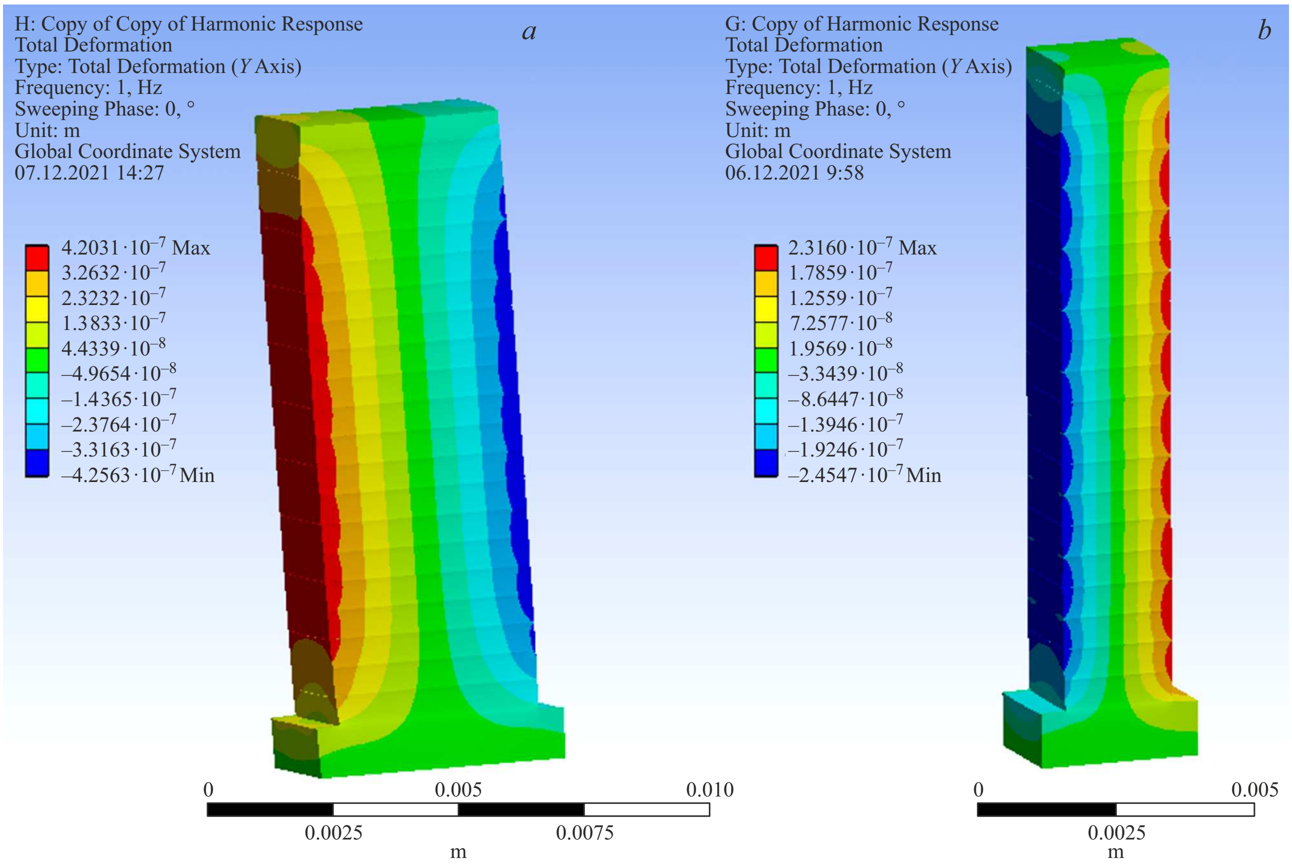

Figure 2. Model of transverse deformation of a piezoceramic actuator containing 20 active layers with an area of $16\,\mathrm{mm}^2$ (*a*) and $4\,\mathrm{mm}^2$ (*b*).

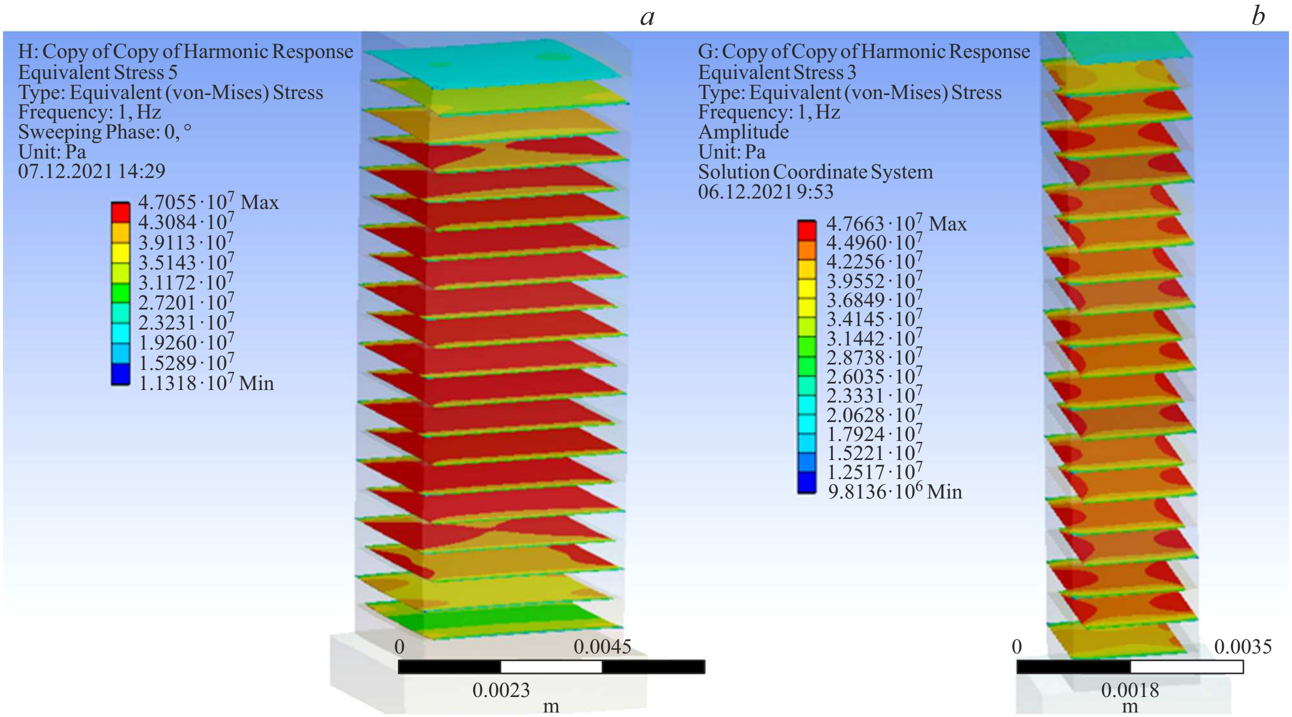

Figure 3. Model of layer-by-layer pressure distribution for actuators with an area of $16\,\mathrm{mm}^2$ (*a*) and $4\,\mathrm{mm}^2$ (*b*).

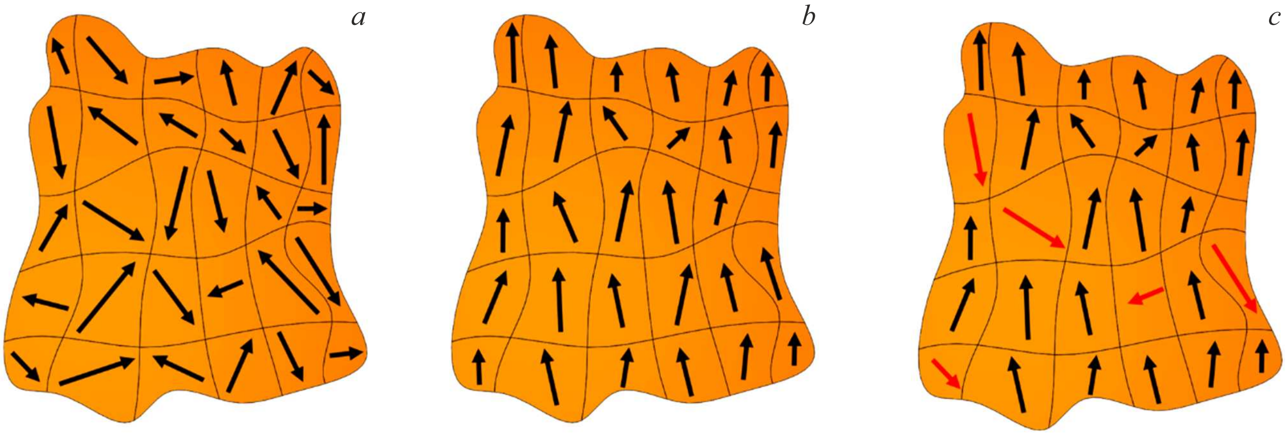

Figure 4. Polarization of domains in a piezoceramic material: (*a*) random distribution, (*b*) ordered distribution, (*c*) effect of lateral mechanical clamping of domains.

service life of piezoelectric elements [22]. Therefore, it was required to use wire switching technology for electrodes in a multilayer actuator package. When analyzing the electrical properties of the developed actuators, it was revealed that at a control voltage of 300 V, the deformation amplitude lies in the range from 4.6 to 4.8 μm. In the model and experimental data, there is a discrepancy in the value of local deformation, since in the manufacture of piezoelements there are a number of factors that affect their performance: the accuracy of deposition of the conductive silver film, the occurrence of local pores in the ceramic material, etc..

Conclusion

During the work, the analysis was carried out by the finite element method on the opportunity of using piezoceramic actuators with a reduced cross-sectional area. Nevertheless, the displacement at a control voltage of 300 V is reduced from 4 μm to 1.5 μm in comparison with multilayer actuators with a larger cross-section due to a decrease in the effective polarization area of piezoelements due to the use of an interelectrode switching method. Therefore, piezoceramic rulers with wire switching were manufactured. In this case, it was possible to increase the displacement at a control voltage of 300 V to the value 4.6–4.8 μm.

The developed piezoelements can be used as control elements for piezoactuator deformable mirrors with high spatial resolution.

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Conflict of interest

The authors declare that they have no conflict of interest.

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