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Dynamics of piezomaterials used in the optical systems

G. Bauriene · A. Fedaravicius · L. Patasiene

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Abstract Complex piezodrives are frequently used in mechanisms of optical systems. They can be bimorph, axial and complex combined stacks. This paper deals with axial piezostacks used in piezoconverters. They make it possible to develop unipolar or bipolar motion which ensures the displacement to be dependent on each piezo-element of the compound stack sections. The bifurcation problem of a piezodrive has been solved by evaluating physical properties of piezoelements in piezostacs and sealing the material. It has made it possible to prove that piezostacs have a lot of static operation possibilities. The original solution of the actuator enabled the choice of optimal initial stresses in piezostacs. The experimental investigation of piezodrives with combined piezostacs has revealed the possibilities to optimize the design and materials for obtaining maximum displacement. These piezodrives may be applied in various systems like gyroscopes and telescopies.

Keywords Piezomaterial · Combined stacks · Displacement · Piezoconverters

1 Introduction

Complex vibration drives are frequently used in the optical of optical systems and are mainly applied for military purposes. They can contribute to the improvement of a variety of extremely precise micro and nano motion systems. According to the calculations the vibration drives of constituent elements tied together by binding material (composite piezoconverters) compose a system with a great static strength. For this reason, such systems are used in mechanisms operating under heavy loads and requiring very precise displacements. The vibration drives used in mechanisms requiring high displacements have indicated that accuracy depends on design and technological factors. Vibration drives can be bimorph, axial and combined stacks. One of the essential requirements for compound vibration drives is their capability to transfer unipolar or bipolar forces. In the first version, the vibration drive acting in one direction is made of separate piezoelements and adapted binding materials. They operate under positive deformation (elongation due to neutral position) when the applied voltage is positive with respect to polarization. The vibration drive returns to its initial position under negative deformation (contraction) when opposite sign voltage is applied to binding materials. Mechanisms of this type are frequently used in adaptive optics. The second version ensures the possibility of displacements to opposite directions from the neutral position–bipolar force. This happens when the vibrodrive elongates from the initial position due to the positive deformation while the defor-mation to the opposite direction occurs as a result of the elastic strain. Piezomotors with a compound vibrodrive are superior over those with a single-layer vibrodrives owing to the fact that by summing up the deformation of each element, the displacement of a compound piezoconverter can be increased. Their mechanical properties are also significantly augmented. Therefore, dynamic characteristics of each individual element of compound piezoconverters have to be determined separately. When assembling the piezoconverter piezoelements with similar characteristics

G. Bauriene · A. Fedaravicius · L. Patasiene (✉)
Institute of Defence Technologies,
Kaunas University of Technology,
Kestucio st.27,
44025 Kaunas, Lithuania
e-mail: laima.patasiene@ktu.lt

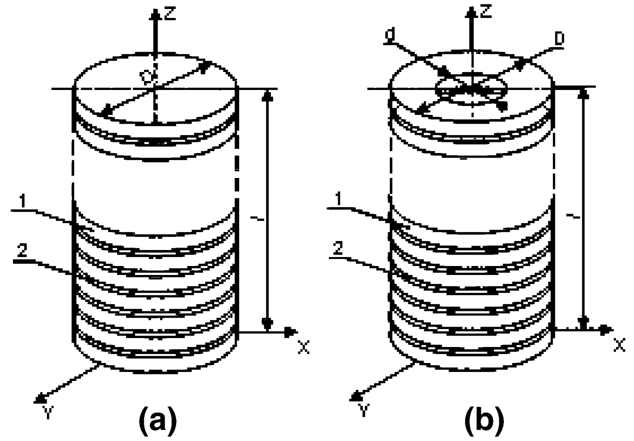

Fig. 1 Piezodrives of constituent elements piezostack containing alternating layers of piezoceramic elements (*1*), and binding material (*2*): (**a**) with disk elements, (**b**) with ring elements

have to be selected. When piezoceramics are deformed by external electric field, the input electrical energy is larger than the output mechanical energy. The ineffective electrical energy is stored as electrostatic energy in the piezoconverter and reverts to the power supply in the final process of an operating cycle.

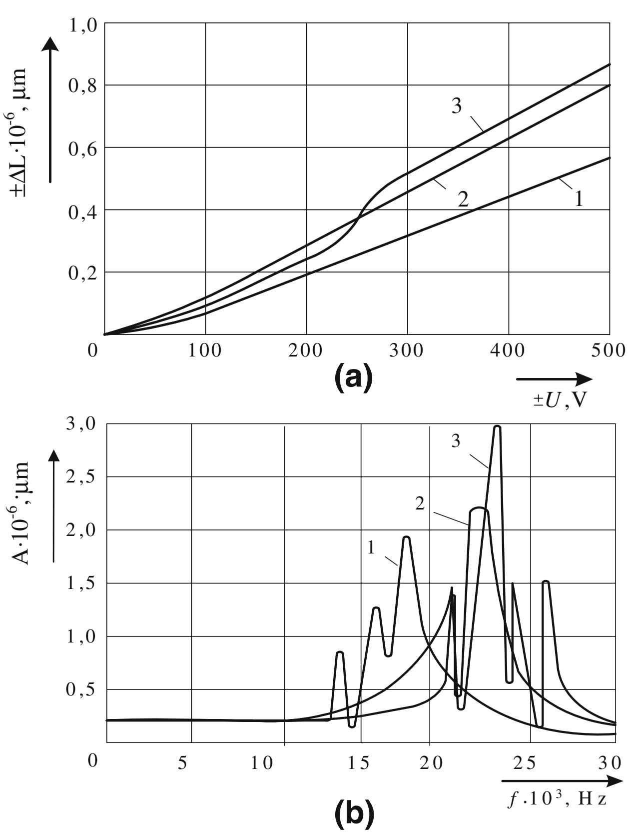

Fig. 2 Dependence of piezoelement on the loading characteristics: (**a**) amplitude; (**b**)frequency

2 The piezoconverters used in mechanisms requiring high precision displacements

Technical possibilities of combined piezostack used in piezoconverters are analyzed and reported in many works [1]. Under severe conditions and environment these structures are to be thoroughly investigated. Mechanical and electrical laws pertaining in combined converters are analysed and their interrelation is written by the mathematical expression:

$$\begin{aligned} \overline{\sigma} &= [c^E]\overline{\varepsilon} - [e]\overline{E} \\ \overline{D} &= [e]^T\overline{\varepsilon} + [\ni^s]\overline{E} \end{aligned} \tag{1}$$

here σ=mechanical stress; D=vector of electric displacement; $[c^E]$=stiffness tensor; $[e]$=tensor of piezoelectric constant; $[\ni^s]$=tensor of dielectric constant.

$$[K_0] = \int\limits_{V^e} [B]^T \left[C^E\right][B]dV \tag{2}$$

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

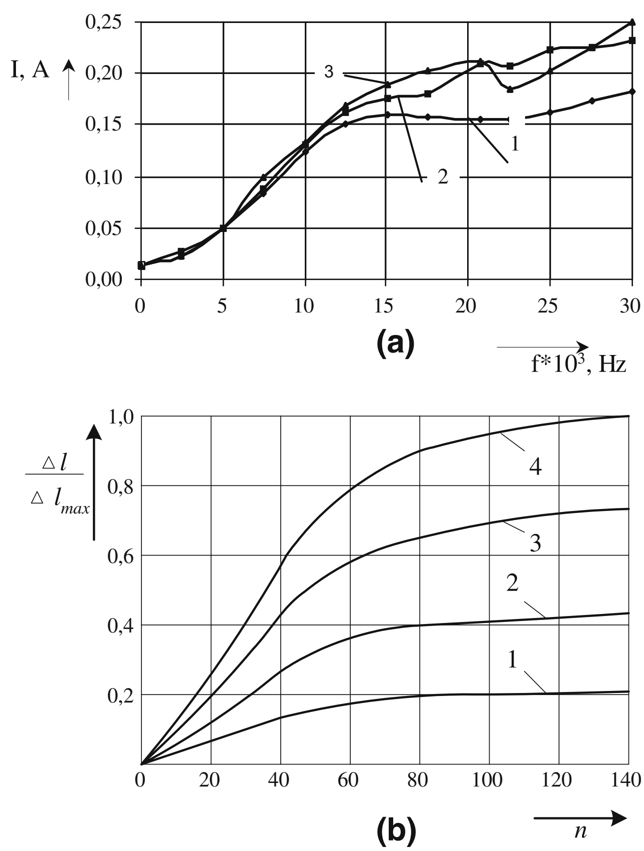

Fig. 3 Dependence of piezostack displacement on (**a**) the frequency of deformations under the forces of 1–700 N, 2–1,200 N, 3–1,500 N and on (**b**) the number of piezoelements when 1-U=100 V, 2-U=200 V, 3-U=300 V, 4-U=400 V

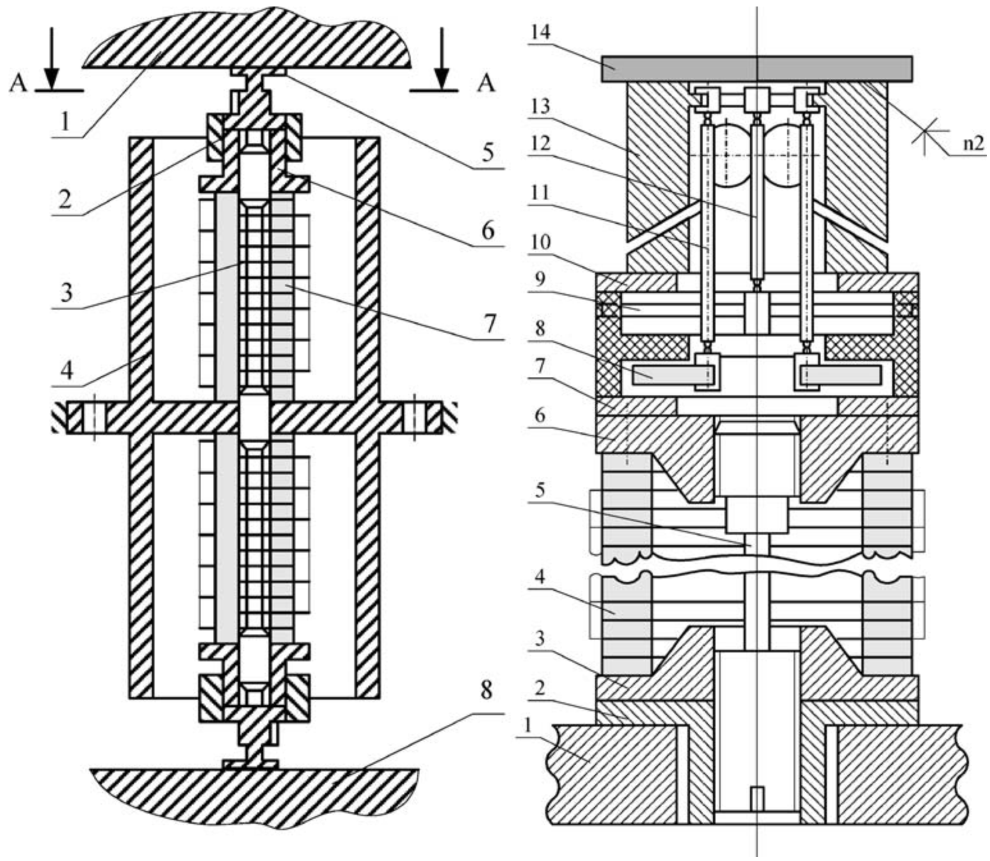

Fig. 4 Piezoconverters used in optical systems

transformation matrix $[B]$ where the matrix $[B]$ is determined by deformations and displacements $\overline{\varepsilon} = [B]\overline{\sigma}^e$:

$$\int_{V^e} d[B_L]^T \{\sigma\} dV = [K_\sigma] d\{\delta\} \tag{3}$$

where $[B_L]^T$ is the transformation matrix $[B_L]$ estimating nonlinearity of deformations, $[K_\sigma]$ is the matrix estimates piezoelectric properties described by formulas Eq. 1. The coefficient of proportionality λ indicates the extent of the load increase in order to obtain critical strength $[\delta]$. The critical load—$P_{kp}=P\lambda$.

Figure 1 shows a high static strength system composed of the piezoconverters of constituent elements tied together by binding material (piezostacks) according to the calculations. The values of critical loads are obtained for piezodrives as follows:

1. with disk elements P_{kp}=280,244.48 N
2. with ring elements P_{kp}=269,455.07 N

For this reason, these systems are used in mechanisms operating under heavy loads and requiring very precise displacements. The piezoactuators used in mechanisms requiring high precision displacements have indicated that their accuracy depends on design and technological factors (Fig. 1).

The piezoactuators have been investigated both under static and dynamic regimes [2]. It should be noted that dependence of the current flowing through the piezostack and on the frequency of piezoelements deformations makes it possible to choose the right power regimes to design excitation and control systems and also to select the optimal mechanical and electrical parameters.

3 Dependence of piezoelement displacement on the loading amplitude and frequency characteristics

The initial tension has been obtained by tightening the piezoelements with a sufficiently elastic pin made of beryllium bronze. Figure 2(a) presents the dependence of piezoelement displacement on the initial tension force. Curves 1, 2 and 3 are obtained by applying tension forces of 20, 150 and 200 N, respectively. Figure 2(b) displays the amplitude-frequency characteristics under different tension forces: 700, 1,200 and 1,500 N.

Piezostacks have been made of different materials however, their manufacturing technology was absolutely identical. In order to get the greatest displacement in a piezodrive the size of the pin and its material is to be taken into account. Experimental investigations of piezostacks have shown that an increase in the number of elements does not increase displacement. Therefore, to determine the dependence of displacement amplitude on the number of piezoelements in a stack, several stacks have been prepared with different number of piezoelements, but applying the same manufacturing technology. The same tension force value has been maintained for all piezostacks, Fig. 3(a). It is evident that beginning with 60 piezoelements an increase in the number of piezoelements has no substantial effect on the stack displacement amplitude. The displacement of a free (not fastened) end of a piezostack on the plane has been analyzed i.e., the value of the deflection from the vertical axis has been determined. The experiment has been made under the supply voltage of 500 V. The piezostacks made in absolutely the same way have been tested and the results indicate that the deflection from their vertical axis is purely random. It has been assumed that dissimilarity of the planes of separate piezoelements is up to 7.3 (minimum value is 3.9) and that it is the cause of motion of the free piezostack end by the complex trajectory, as well as undesirable deformations along the entire length of a stack. Then the conclusion has been made that the main displacement is produced by the bottom part of the piezostack, while the upper part (approximately 1/3 of its height) develops deformations of negligible usefulness. In addition to the investigation results shown in Fig. 3(b) this fact admonishes that precaution should be taken when choosing the number of piezoelements for obtaining the higher displacement amplitude. The desired displacement value can be achieved with lower power and labour expenditure if the optimal number of piezoelements is selected and manufacturing conditions are observed which do not restrict the displacement value but restrict the deflection of piezostack from the vertical axis (Fig. 3).

4 Piezostacs used in optical systems

The ineffective electrical energy is stored as electrostatic energy in the piezoceramics material and reverts it to the power supply in the final process of an operating cycle. The analyzed criteria have made it possible to choose the piezomaterial for an optimal construction having a maximum displacement. Figure 4(a) presents the design of a piezodrive used for the control of a telescope secondary mirror. It consists of two piezostacks 7 installed in frame 4 with the initial stress developed by pin 3. The pin piercing both piezopackets is fixed at caps 6 to which flexible hinges 5 are screwed by nuts 2. Mirror 8 and equalizer 1 are located at equal distances in opposite directions. The combined piezodrive design is illustrated in Fig. 4(b). It ensures three degrees of freedom to a slid-over object. The piezodrive consists of two rigidly connected parts. At the bottom there is piezostack 4 with the initial stress developed by pin 5, a cap consisting of intermediate disk 3 and plate 7 and also base 2 elastically connected to brick 1. The upper part has two pairs of bimorphs 8 and 9 installed in the frame it is elastically connected to the frame by plate 10. By means of rods 11 and 12 the bimorphs are connected to the hinges and the motion is transmitted to the mirror through hinge 13. The bottom part of the piezodrive ensures the object displacement up to 0.1 mm, while the upper part exerts the angular displacement in two coordinates whose amplitude reaches 0.2 in the frequency range of 0–1,000 Hz (Fig. 4).

5 Conclusion

Investigation of piezomaterials and dynamic experiments of their structural parts have indicated that loading forces and increase in the initial tension decrease harmonic components of fluctuations. Natural frequencies of the piezostack significantly decrease with an increase in the number of piezoelements. Experimental investigation of compound piezostacks make it possible to determine optimal initial tension force, the dependence of displacement of a loose piezostack on some constructional and technological parameters.

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