ISSN: 2476-2334

Research Article

International Journal of Nanotechnology & Nanomedicine

Structural-Parametric Model Electroelastic Actuator of Mechatronics Systems for Nanotechnology and Nanomedicine

Sergey M Afonin*

Department of Intellectual Technical Systems, National Research University of Electronic Technology (MIET)

***Corresponding author**
Sergey M Afonin Department of Intellectual Technical Systems, National Research University of Electronic Technology (MIET), 124498 Moscow, Russia, National Research University of Electronic Technology (MIET)
E-mail: learner01@mail.ru

Submitted: 09 Sep 2017; **Accepted**: 31 Oct 2017; **Published**: 25 Jan 2018

Abstract
Structural-parametric model, decision of wave equation, parametric structural schematic diagram, transfer functions of the electroelastic actuator of mechatronics systems for nanotechnology and nanomedicine are obtained. Effects of geometric and physical parameters of the piezoactuator and the external load on its dynamic characteristics are determined. The parametric structural schematic diagram and the transfer functions of the piezoactuator for the transverse, longitudinal, shift piezoelectric effects are obtained from the structural-parametric model of the piezoactuator. For calculation of the control systems for nanotechnology with the piezoactuator its the parametric structural schematic diagram and the transfer functions are determined. The generalized parametric structural schematic diagram of the electroelastic actuator is constructed.

Keywords: Structural-parametric model; Parametric structural schematic diagram; Decision wave equations; Electroelastic actuator; Piezoactuator; Deformation; Transfer functions

Introduction
For nanotechnology, nanomedicine, nanobiology, power engineering, microelectronics, astronomy for large compound telescopes, antennas satellite telescopes and adaptive optics equipment is promising for use mechatronics systems with electromechanical actuators based on electroelasticity (piezoelectric effect). Piezoelectric actuator (piezoactuator) - piezomechanical device intended for actuation of mechanisms, systems or management based on the piezoelectric effect, converts electrical signals into mechanical movement or force [1-5].

In the present work is solving the problem of building the structural parametric model of the electroelastic actuator in contrast electrical equivalent circuits Cady and Mason for calculation of piezoelectric transmitter and receiver [6-9]. Consider building the structural-parametric model of the piezoactuator, representing the system of equations, which, given the electromechanical parameters of the piezoactuator describes the structure and conversion the energy electric field into mechanical energy and the corresponding displacements and forces at its the ends. By solving the wave equation with allowance methods of mathematical physics using Laplace transform and the equation of piezoelectric effect, the boundary conditions on working surfaces of the piezoactuator, the strains along the coordinate axes, it is possible to construct a structural-parametric model of the piezoactuator. The transfer functions and the parametric structural schematic diagrams of the electroelastic actuator are obtained from its structural-parametric model [3-14].

The piezoactuator of nano- and micrometric movements for mechatronics systems operates based on the inverse piezoeffect, in which the motion is achieved due to deformation of the piezoelement when an external electric voltage is applied to it. Piezoactuator for drives of nano- and micrometric movements provide a movement range from several nanometers to tens of micrometers, a sensitivity of up to 10 nm/V, a loading capacity of up to 1000 N, a ransmission band of up to 100 Hz. Piezoactuator provide high stress and speed of operation and return to the initial state when switched off. The use of piezoactuators solves the problems of precise alignment and compensation of temperature and gravitational deformations in nanotechnology. Piezoactuator is used in the majority mechatronic systems of nanotechnology and nanomedicine for scanning tunneling microscopes, scanning force microscopes atomic force microscopes [11-16].

Decision wave equation and structural-parametric model of electroelastic actuator
Since the deformation of the electroelastic actuator corresponds to its stressed state, therefore in the piezoactuator there are six stress components $T_1, T_2, T_3, T_4, T_5, T_6$, where the components T_1, T_2, T_3 are related to extension-compression stresses and T_4, T_5, T_6 to shear stresses.

The matrix state equations [8] connecting the electric and elastic variables for polarized piezoceramics have the following form:

$$\mathbf{D}=\mathbf{d}\mathbf{T}+\boldsymbol{\varepsilon}^{T}\mathbf{E}, \qquad (1)$$

$$\mathbf{S}=\mathbf{s}^{E}\mathbf{T}+\mathbf{d}^{t}\,\mathbf{E}_{r}, \qquad (2)$$

where the first equation describes the direct piezoelectric effect, and the second - the inverse piezoelectric effect; **D** is the column matrix of electric induction along the coordinate axes; **S** is the column matrix of relative deformations; **T** is the column matrix of mechanical stresses; **E** is the column matrix of electric field strength along the coordinate axes; $\mathbf{s}^{E}$ is the elastic compliance matrix for E=const ; $\boldsymbol{\varepsilon}^{T}$ is the matrix of dielectric constants for T=const ; $\mathbf{d}^{t}$ is the the transposed matrix of the piezoelectric modules.

In polarized piezoceramics from lead zirconate titanate PZT for a piezoactuator there are five independent components s_{11}^{E}, s_{12}^{E}, s_{13}^{E}, s_{33}^{E}, s_{55}^{E} in the elastic compliance matrix, three independent components d_{33}, d_{31}, d_{15} in the transposed matrix of the piezoelectric modules and three independent components ε_{11}^{T}, ε_{22}^{T}, ε_{33}^{T} in the matrix of dielectric constants. Let us consider the simplest piezoactuator in Figure 1 for longitudinal, transverse and shift deformations.

Let us consider the piezoactuator for the longitudinal piezoelectric effect, where δ is thickness and the electrodes deposited on its faces perpendicular to axis 3, the area of which is equal to S_0. The direction of the polarization axis P, i.e., the direction along which polarization was performed, is usually taken as the direction of axis 3. The equation of the inverse longitudinal piezoelectric effect has the form [8,12].

$$S_3 = d_{33}E_3(t) + s_{33}^{E}T_3(x,t)\,, \qquad (3)$$

where $S_3=\partial\xi(x,t)/\partial x$ is the relative displacement of the cross section of the piezoactuator, d_{33} is the piezomodule for the longitudinal piezoeffect, $E_3(t) = U(t)/\delta$ is the electric field strength, $U(t)$ is the voltage between the electrodes of actuator, δ is the thickness, s_{33}^{E} is the elastic compliance along axis 3, and T_3 is the mechanical stress along axis 3.

The equation of equilibrium for the forces acting on the piezoactuator (the piezoelectric plate) on **Figure 1** can be written as

$$T_3 S_0 = F + M\frac{\partial^2\xi(x,t)}{\partial t^2}, \qquad (4)$$

where F is the external force applied to the piezoactuator, S_0 is the cross section area and M is the displaced mass.

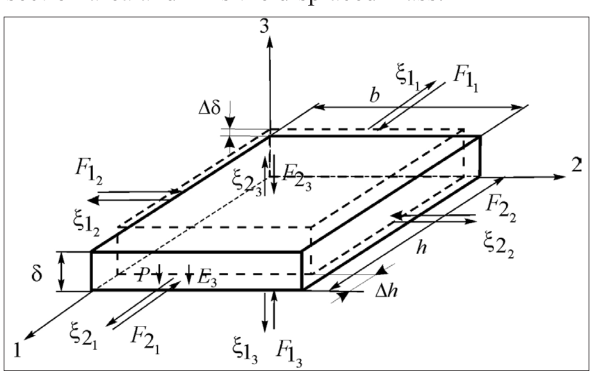

Figure 1: Piezoactuator.

For constructing a structural parametric model of the voltage-controlled electroelastic actuator, let us solve simultaneously the wave equation using Laplace transform, the equation of the inverse longitudinal piezoeffect, the equation of forces acting on the faces of the piezoactuator.

Calculations of the piezoactuators are performed using a wave equation describing the wave propagation in a long line with damping but without distortions, which can be written in the form [8,11,12].

$$\frac{1}{(c^E)^2}\frac{\partial^2\xi(x,t)}{\partial t^2}+\frac{2\alpha}{c^E}\frac{\partial\xi(x,t)}{\partial t}+\alpha^2\xi(x,t)=\frac{\partial^2\xi(x,t)}{\partial x^2}, \qquad (5)$$

where $\xi(x,t)$ is the displacement of the section, x is the coordinate, t is time, c^E is the sound speed for, E = const, α is the damping coefficient.

Using Laplace transform, we can reduce the original problem for the partial differential hyperbolic equation of type (5) to a simpler problem for the linear ordinary differential equation [10,12].

Applying the Laplace transform to the wave equation (5)

$$\Xi(x,p) = L\{\xi(x,t)\} = \int_0^{\infty}\xi(x,t)e^{-pt}dt\,, \qquad (6)$$

and setting the zero initial conditions.
We obtain the linear ordinary second-order differential equation with the parameter p

$$\frac{d^2\Xi(x,p)}{dx^2}-\left[\frac{1}{(c^E)^2}p^2+\frac{2\alpha}{c^E}p+\alpha^2\right]\Xi(x,p)=0\,, \qquad (7)$$

with its solution being the function

$$\Xi(x,p) = Ce^{-x\gamma} + Be^{x\gamma} \qquad (8)$$

where $\Xi(x,p)$ is the Laplace transform of the displacement of the section of the piezoelectric actuator, $\gamma = p/c^E + \alpha$ is the propagation coefficient.

We denote

$\Xi(0,p) = \Xi_1(p)$ for x=0, (9)

$\Xi(\delta,p) = \Xi_2(p)$ for $x=\delta$,

Then we get the coefficients C and B

$$C = \left(\Xi_1 e^{\delta\gamma} - \Xi_2\right)/\left[2\mathrm{sh}(\delta\gamma)\right],\; B = -\left(\Xi_1 e^{-\delta\gamma} - \Xi_2\right)/\left[2\mathrm{sh}(\delta\gamma)\right]. \qquad (10)$$

The solution (7) can be written as

$$\Xi(x,p) = \left\{\Xi_1(p)\mathrm{sh}\left[(\delta - x)\gamma\right] + \Xi_2(p)\mathrm{sh}(x\gamma)\right\}/\mathrm{sh}(\delta\gamma). \qquad (11)$$

The equations for the forces on the faces of the piezoactuator

$$T_3(0,p)S_0 = F_1(p) + M_1 p^2\Xi_1(p) \quad \text{for} \quad x = 0 \qquad (12)$$

$$T_3(\delta,p)S_0 = -F_2(p) - M_2 p^2\Xi_2(p) \quad \text{for} \quad x = \delta\,,$$

where $T_3(0,p)$ and $T_3(\delta,p)$ are determined from the equation of the inverse piezoelectric effect.

For $x = 0$ and $x = \delta$, we obtain the set of equations for determining stresses in the piezoactuator [11 - 14]:

$$T_3(0,p) = \frac{1}{s_{33}^E}\frac{d\Xi(x,p)}{dx}\bigg|_{x=0} - \frac{d_{33}}{s_{33}^E}E_3(p),$$
$$T_3(\delta,p) = \frac{1}{s_{33}^E}\frac{d\Xi(x,p)}{dx}\bigg|_{x=\delta} - \frac{d_{33}}{s_{33}^E}E_3(p). \quad (13)$$

The set of equations (13) yield the set of equations for the structural-parametric model of the piezoactuator and parametric structural schematic diagram of a voltage-controlled piezoactuator for longitudinal piezoelectric effect on **Figure 2**

$$\Xi_1(p) = \left[1/\left(M_1 p^2\right)\right]\cdot \left\{-F_1(p) + \left(1/\chi_{33}^E\right)\left[d_{33}E_3(p) - \left[\gamma/\mathrm{sh}(\delta\gamma)\right]\left[\mathrm{ch}(\delta\gamma)\Xi_1(p) - \Xi_2(p)\right]\right]\right\}, \quad (14)$$

$$\Xi_2(p) = \left[1/\left(M_2 p^2\right)\right]\cdot \left\{-F_2(p) + \left(1/\chi_{33}^E\right)\left[d_{33}E_3(p) - \left[\gamma/\mathrm{sh}(\delta\gamma)\right]\left[\mathrm{ch}(\delta\gamma)\Xi_2(p) - \Xi_1(p)\right]\right]\right\},$$

where $\chi_{33}^E = s_{33}^E/S_0$.

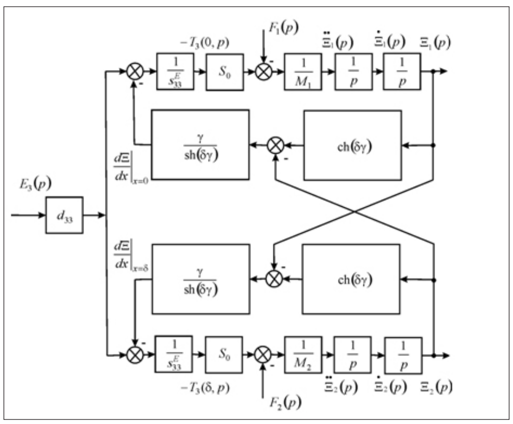

Figure 2: Parametric structural schematic diagram of a voltage-controlled piezoactuator for longitudinal piezoelectric effect.

From (2), (3), (14) we obtain the system of equations describing the generalized structural-parametric model of the electroelastic actuator

$$\Xi_1(p) = \left[1/\left(M_1 p^2\right)\right]\cdot \left\{-F_1(p) + \left(1/\chi_{ij}^\Psi\right)\left[d_{mi}\Psi_m(p) - \left[\gamma/\mathrm{sh}(l\gamma)\right]\left[\mathrm{ch}(l\gamma)\Xi_1(p) - \Xi_2(p)\right]\right]\right\} \quad (15)$$

$$\Xi_2(p) = \left[1/\left(M_2 p^2\right)\right]\cdot \left\{-F_2(p) + \left(1/\chi_{ij}^\Psi\right)\left[d_{mi}\Psi_m(p) - \left[\gamma/\mathrm{sh}(l\gamma)\right]\left[\mathrm{ch}(l\gamma)\Xi_2(p) - \Xi_1(p)\right]\right]\right\}$$

where $d_{mi} = \begin{cases} d_{33}, d_{31}, d_{15} \\ g_{33}, g_{31}, g_{15} \end{cases}$, $\Psi_m = \begin{cases} E_3, E_3, E_1 \\ D_3, D_3, D_1 \end{cases}$,

$s_{ij}^\Psi = \begin{cases} s_{33}^E, s_{11}^E, s_{55}^E \\ s_{33}^D, s_{11}^D, s_{55}^D \end{cases}$, $l = \{\delta, h, b$, $c^\Psi = \{c^E, c^D$, $\gamma^\Psi = \{\gamma^E, \gamma^D$,

$\chi_{ij}^\Psi = s_{ij}^\Psi/S_0$, $i = 1, 2, \ldots, 6$, $j = 1, 2, \ldots, 6$, $m = 1, 2, 3$,

then parameter Ψ of the control parameter for the piezoactuator: E for voltage control, D for current control. On Figure 3 is shown the generalized parametric structural schematic diagram of the electroelastic actuator corresponding to the set (15) of equations.

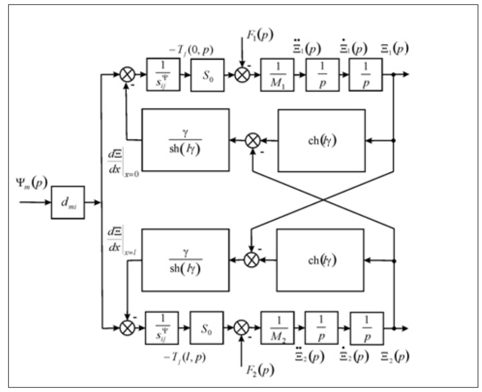

Figure 3: Generalized parametric structural schematic diagram of the electroetoelastic actuator.

Transfer functions of electroelastic actuator

From generalized structural-parametric model (15) of the electroelastic actuator after algebraic transformations we obtain the transfer functions in matrix form [11 - 14], where the transfer functions are the ratio of the Laplace transform of the displacement of the face piezoactuator and the Laplace transform of the corresponding control parameter or force at zero initial conditions.

$$\Xi_1(p) = W_{11}(p)\Psi_m(p) + W_{12}(p)F_1(p) + W_{13}(p)F_2(p), \quad (16)$$
$$\Xi_2(p) = W_{21}(p)\Psi_m(p) + W_{22}(p)F_1(p) + W_{23}(p)F_2(p),$$

where the generalized transfer functions of the piezoactuator are

$$W_{11}(p) = \Xi_1(p)/\Psi_m(p) = d_{mi}\left[M_2\chi_{ij}^\Psi p^2 + \gamma\,\mathrm{th}(l\gamma/2)\right]/A_{ij},$$
$$A_{ij} = M_1M_2\left(\chi_{ij}^\Psi\right)^2 p^4 + \left\{(M_1+M_2)\chi_{ij}^\Psi/\left[c^\Psi\,\mathrm{th}(l\gamma)\right]\right\}p^3 +$$
$$\left[(M_1+M_2)\chi_{ij}^\Psi\alpha/\mathrm{th}(l\gamma) + 1/\left(c^\Psi\right)^2\right]p^2 + 2\alpha p/c^\Psi + \alpha^2,$$
$$W_{21}(p) = \Xi_2(p)/\Psi_m(p) = d_{mi}\left[M_1\chi_{ij}^\Psi p^2 + \gamma\,\mathrm{th}(l\gamma/2)\right]/A_{ij},$$
$$W_{12}(p) = \Xi_1(p)/F_1(p) = -\chi_{ij}^\Psi\left[M_2\chi_{ij}^\Psi p^2 + \gamma/\mathrm{th}(l\gamma)\right]/A_{ij},$$
$$W_{13}(p) = \Xi_1(p)/F_2(p) =$$
$$W_{22}(p) = \Xi_2(p)/F_1(p) = \left[\chi_{ij}^\Psi\gamma/\mathrm{sh}(l\gamma)\right]/A_{ij},$$
$$W_{23}(p) = \Xi_2(p)/F_2(p) = -\chi_{ij}^\Psi\left[M_1\chi_{ij}^\Psi p^2 + \gamma/\mathrm{th}(l\gamma)\right]/A_{ij}.$$

We obtain from equations (15) the generalized matrix equaion for the electroelastic actuator

$$\begin{pmatrix}\Xi_1(p)\\ \Xi_2(p)\end{pmatrix} = \begin{pmatrix}W_{11}(p) & W_{12}(p) & W_{13}(p)\\ W_{21}(p) & W_{22}(p) & W_{23}(p)\end{pmatrix}\begin{pmatrix}\Psi_m(p)\\ F_1(p)\\ F_2(p)\end{pmatrix}. \quad (17)$$

Let us find the displacement of the faces piezoactuator in a stationary regime for inertial load at $\Psi_m(t) = \Psi_{m0}\cdot 1(t)$, $F_1(t) = F_2(t) = 0$.

Then we get the static displacement of the faces piezoactuator

$$\xi_1(\infty)=\lim_{t\to\infty}\xi_1(t)=\lim_{\substack{p\to 0\\ \alpha\to 0}} pW_{11}(p)\Psi_{m0}/p =$$
$$d_{mi}l\Psi_{m0}\left(M_2+m/2\right)/\left(M_1+M_2+m\right), \quad (18)$$

$$\xi_2(\infty)=\lim_{t\to\infty}\xi_2(t)=\lim_{\substack{p\to 0\\ \alpha\to 0}} pW_{21}(p)\Psi_{m0}/p =$$
$$d_{mi}l\Psi_{m0}\left(M_1+m/2\right)/\left(M_1+M_2+m\right), \quad (19)$$

$$\xi_1(\infty)+\xi_2(\infty)=\lim_{t\to\infty}(\xi_1(t)+\xi_2(t))=d_{mi}l\Psi_{m0}, \quad (20)$$

where m is the mass of the piezoactuator, M_1, M_2 are the load masses.

Let us consider a numerical example of the calculation of static characteristics of the piezoactuator from piezoceramics PZT under the longitudinal piezoelectric effect at $m<<M_1$ and $m<<M_2$. For $d_{33}= 4\cdot 10^{-10}$ m/V, U=125 V, M_1= 1kg and M_2 = 4kg we obtain the static displacement of the faces of the piezoactuator $\xi_1(\infty)$ =40 nm, $\xi_2(\infty)$= 10 nm, $\xi_1(\infty)+\xi_2(\infty)$ = 50 nm.

The static displacement the faces of the piezoactuator for the transverse piezoelectric effect and inertial load at $U(t)=U_0\cdot 1(t)$, $E_3(t)=E_{30}\cdot 1(t)=(U_0/\delta)\cdot 1(t)$ and $F_1(t)=F_2(t)=0$ can be written in the following from

$$\xi_1(\infty)=\lim_{t\to\infty}\xi_1(t)=\lim_{\substack{p\to 0\\ \alpha\to 0}} pW_{11}(p)(U_0/\delta)/p = \quad (21)$$
$$d_{31}(h/\delta)U_0\left(M_2+m/2\right)/\left(M_1+M_2+m\right),$$

$$\xi_2(\infty)=\lim_{t\to\infty}\xi_2(t)=\lim_{\substack{p\to 0\\ \alpha\to 0}} pW_{21}(p)(U_0/\delta)/p = \quad (22)$$
$$d_{31}(h/\delta)U_0\left(M_1+m/2\right)/\left(M_1+M_2+m\right)$$

$$\xi_1(\infty)+\xi_2(\infty)=\lim_{t\to\infty}(\xi_1(t)+\xi_2(t))=d_{31}(h/\delta)U_0. \quad (23)$$

From (21), (22) we obtain the static displacement of the faces of the piezoactuator for the transverse piezoeffect at $m<<M_1$, $m<<M_2$ in the form

$$\xi_1(\infty)=\lim_{t\to\infty}\xi_1(t)=\lim_{\substack{p\to 0\\ \alpha\to 0}} pW_{11}(p)(U_0/\delta)/p = \quad (24)$$
$$d_{31}(h/\delta)U_0\, M_2/\left(M_1+M_2\right),$$

$$\xi_2(\infty)=\lim_{t\to\infty}\xi_2(t)=\lim_{\substack{p\to 0\\ \alpha\to 0}} pW_{21}(p)(U_0/\delta)/p =$$
$$d_{31}(h/\delta)U_0\, M_1/\left(M_1+M_2\right). \quad (25)$$

Let us consider a numerical example of the calculation of static characteristics of the piezoactuator from piezoceramics PZT under the transverse piezoelectric effect at $m<<M_1$ and $m<<M_2$.

For $d_{31}= 2\cdot 10^{-10}$ m/V, h=4·10^{-2} m, $\delta = 2\cdot 10^{-3}$ m, U=100 V, M_1=1 kg and M_2= 4kg we obtain the static displacement of the faces of the piezoelectric actuator $\xi_1(\infty)$=320 nm, ξ_2 = 80nm (∞), $\xi_1(\infty)+\xi_2(\infty)$ =400 nm.

From (16) we obtain the transfer functions of the piezoactuator with a fixed end and elastic inertial load so that $M_1\to\infty$ and $m<<M_2$ in the following form

$$W_2(p)=\frac{\Xi_2(p)}{U(p)}=\frac{d_{33}}{\left(1+C_e/C_{33}^E\right)\left(T_t^2p^2+2T_t\xi_t p+1\right)}, \quad (26)$$

where the time constant T_t and the damping coefficient ξ_t are determined by the formulas

$$T_t=\sqrt{M_2/\left(C_e+C_{33}^E\right)},\ \xi_t=\alpha\delta^2C_{33}^E\Big/\left(3c^E\sqrt{M_2\left(C_e+C_{33}^E\right)}\right)$$

Let us consider the operation at low frequencies for the piezoactuator from piezoceramics PZT with one face rigidly fixed and elastic inertial load so that $M_1\to\infty$ and $m<<M_2$ for M_2=10 kg, C_{33}=2.4·10^6 N/m, C_e = 0.1·10^6 N/m, we obtain T_t = 2·10^{-3} c. The experimental and calculated values for the piezoactuator are in agreement to an accuracy of 5%.

Conclusions

Structural-parametric model, decision of wave equation, parametric structural schematic diagram, transfer functions of the electroelastic actuator are obtained using Laplace transform. The parametric structural schematic diagram and the transfer functions of the piezoactuator for the transverse, longitudinal, shift piezoelectric effects are determined from the structural-parametric model of the electroelastic actuator. The transfer functions in matrix form are describe deformations of the piezoactuator during its operation as a part of mechatronics systems for nanotechnoly and nanomedicine.

From the decision of the wave equation and the features of the deformations along the coordinate axes we obtain the generalized structural-parametric model and the parametric structural schematic diagram of the electroelastic actuator for mechatronics systems and its dynamic and static properties.

References

1. Schultz J, Ueda J, Asada H (2017) Cellular Actuators. Oxford: Butterworth-Heinemann Publisher, 382 p.
2. Uchino K (1997) Piezoelectric Actuator and Ultrasonic Motors. Boston, MA: Kluwer Academic Publisher, 347 p.
3. Afonin SM (2006) Solution of the wave equation for the control of an elecromagnetoelastic transduser. Doklady mathematics. 73(2): 307-313, doi:10.1134/S1064562406020402.
4. Afonin SM (2008) Structural parametric model of a piezoelectric nanodisplacement transduser. Doklady physics. 53(3): 137-143, doi:10.1134/S1028335808030063.
5. Afonin SM (2014) Stability of strain control systems of nano- and microdisplacement piezotransducers. Mechanics of solids. 49(2); 196-207, doi:10.3103/S0025654414020095.
6. Talakokula V, Bhalla S, Ball RJ, Bowen CR, Pesce GL, Kurchania R, Bhattacharjee B, Gupta A, Paine K (2016) Diagnosis of carbonation induced corrosion initiation and progressionin reinforced concrete structures using piezo-impedance transducers. Sensors and Actuators A: Physical. 242: 79-91, doi: 10.1016/j.sna.2016.02.033.
7. Cady WG (1946) Piezoelectricity: An introduction to the theory and applications of electromechancial phenomena in crystals. New York, London: McGraw-Hill Book Company, 806 p.
8. Mason W editor (1964) Physical Acoustics: Principles and

Methods. Vol. 1. Part A. Methods and Devices. New York: Academic Press. 515 p.
9. Yang Y, Tang L (2009) Equivalent circuit modeling of piezoelectric energy harvesters. Journal of intelligent material systems and structures. 20(18): 2223-2235.
10. Zwillinger D (1989) Handbook of Differential Equations. Boston: Academic Press. 673 p.
11. Afonin SM (2015) Structural-parametric model and transfer functions of electroelastic actuator for nano- and microdisplacement. Chapter 9 in Piezoelectrics and Nanomaterials: Fundamentals, Developments and Applications. Parinov IA editor. New York: Nova Science, pp. 225-242.
12. Afonin SM (2005) Generalized parametric structural model of a compound elecromagnetoelastic transduser. Doklady physics. 50(2): 77-82, doi:10.1134/1.1881716.
13. Afonin SM (2002) Parametric structural diagram of a piezoelectric converter. Mechanics of solids. 37(6): 85-91.
14. Afonin SM (2015) Block diagrams of a multilayer piezoelectric motor for nano- and microdisplacements based on the transverse piezoeffect. Journal of computer and systems sciences international. 54(3): 424-439, doi: 10.1134/S1064230715020021.
15. Bhushan B editor (2004) Springer Handbook of Nanotechnology. New York: Springer, 1222 p.
16. Nalwa HS editor (2004) Encyclopedia of Nanoscience and Nanotechnology. Calif.: American Scientific Publishers.