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Electromagnetelastic Actuator for Nanomechanics

By Afonin SM
National Research University of Electronic Technology

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I. INTRODUCTION

The electromagnetoelastic actuator for piezoelectric, piezomagnetic, electrostriction, magnetostriction effects is used for the precise adjustment in the nanomechanics, the nanotechnology, the adaptive optics [1–32]. The piezoactuator on the inverse piezoeffect is serves for the actuation of mechanisms or the management, converts the electrical signals into the displacement and the force [1–8]. The piezoactuator for the nanomechanics is provided the displacement from nanometers to tens of micrometers, a force to 1000 N. The piezoactuator is used in the nanomechanics and the nanotechnology for the scanning tunneling microscopes, the scanning force microscopes and the atomic force microscopes [14–32].

In the present paper the generalized structural-parametric model and the generalized parametric structural schematic diagram of the electromagnetoelastic actuator are constructed by solving the equation of the electromagnetolasticity, the wave equation with the Laplace transform, the boundary conditions on loaded working surfaces of the actuator, the strains along the coordinate axes. The transfer functions and the parametric structural schematic diagrams of the piezoactuator are obtained from the generalized structural-parametric model. In [6, 7] was determined the solution of the wave equation of the piezoactuator. In the [14–16, 30] were obtained the structural-parametric models, the schematic diagrams for simple piezoactuator and this models were transformed to the structural-parametric model of the electromagnetoelastic actuator. The structural-parametric model of the electroelastic actuator was determined in contrast electrical equivalent circuit for calculation of piezoelectric transmitter and receiver [9–12]. In [8, 27] was used the transfer functions of the piezoactuator for the decision problem absolute stability conditions for a system controlling the deformation of the electromagnetoelastic actuator. The elastic compliances and the mechanical and adjusting characteristics of the piezoactuator were found in [18, 21 – 23, 28, 29] for calculation its transfer functions and the structural-parametric models. The structural-parametric model of the multilayer and compound piezoactuator was determined in [18–20]. In this paper is solving the problem of building the generalized structural parametric model and the generalized parametric structural schematic diagram of the electromagnetoelastic actuator for using the equation of electromagnetoelasticity.

II. STRUCTURAL-PARAMETRIC MODEL

The general structural-parametric model and the parametric structural schematic diagram of the electromagnetoelastic actuator are obtained. In the electroelastic actuator are presented six stress components T_1, T_2, T_3, T_4, T_5, T_6, the components T_1 – T_3 are related to extension-compression stresses, T_4 – T_6 to shear stresses. For the electroelastic actuator its deformation corresponds to stressed state. In piezoceramics PZT the matrix state equations [12, 14] connected the electric and elastic variables have the form two equations, then the first equation describes the direct piezoelectric effect, the second - the inverse piezoelectric effect

$$\mathbf{D} = \mathbf{dT} + \boldsymbol{\varepsilon}^T \mathbf{E} \tag{1}$$

$$\mathbf{S} = \mathbf{s}^E \mathbf{T} + \mathbf{d}^t \mathbf{E} \tag{2}$$

where $\mathbf{D}$ is the column matrix of electric induction; $\mathbf{S}$ is the column matrix of relative deformations; $\mathbf{T}$ is the column matrix of mechanical stresses; $\mathbf{E}$ is the column matrix of electric field strength; $\mathbf{s}^E$ is the elastic compliance matrix for $E = \text{const}$; $\boldsymbol{\varepsilon}^T$ is the matrix of dielectric constants for $T = \text{const}$; $\mathbf{d}^t$ is the transposed matrix of the piezoelectric modules.

The piezoactuator (piezoplate) has the following properties: δ is the thickness, h is the height, b is the

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Author: National Research University of Electronic Technology (Moscow Institute of Electronic Technology, MIET), Moscow, Russia.
e-mail: learner01@mail.ru

width, respectively $l = \{\delta, h, b$ the length of the piezoactuator for the longitudinal, transverse and shift piezoeffects. 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 piezoeffect for controlling voltage [6, 12] has the form

$$S_i = d_{mi}\Psi_m(t) + s_{ij}^{\Psi} T_j(x,t)$$
$$S_i = \partial\xi(x,t)/\partial x\,,\ \ \Psi_m(t) = E_m(t) = U(t)/\delta \qquad (3)$$

where S_i is the relative displacement of the cross section of the piezoactuator along axis *i*, $\Psi_m(t)$ is the control parameter along axis *m*, d_{mi} is the coefficient of the electromagnetolasticity (for example the piezomodule), $E_m(t)$ is the electric field strength along axis *m*, $U(t)$ is the voltage between the electrodes of actuator, s_{ij}^{Ψ} is the elastic compliance for $\Psi = \text{const}$, $T_j(x,t)$ is the mechanical stress along axis *j* and *i, j* = 1, 2, … , 6; *m* = 1, 2, 3. The main size $l = \{\delta, h, b$ for the piezoactuator is respectively, the thickness, the height, the width for the longitudinal, transverse, shift piezoeffects.

For calculation of actuator is used the wave equation [6, 7, 12, 14] for the wave propagation in a long line with damping but without distortions. After Laplace transform is obtained the linear ordinary second-order differential equation with the parameter *p*, whereupon the original problem for the partial differential hyperbolic equation of type using the Laplace transform is reduced to the simpler problem [6, 13] for the linear ordinary differential equation

$$\frac{d^2\Xi(x,p)}{dx^2} - \gamma^2\Xi(x,p) = 0 \qquad (4)$$

with its solution

$$\Xi(x,p) = Ce^{-x\gamma} + Be^{x\gamma} \qquad (5)$$

where $\Xi(x,p)$ is the Laplace transform of the displacement of the section of the piezoactuator, $\gamma = p/c^{\Psi} + \alpha$ is the propagation coefficient, c^{Ψ} is the sound speed for $\Psi = \text{const}$, α is the damping coefficient of the wave, Ψ is the control parameter: *E* is the electric field strength for the voltage control, *D* is the electrical induction for the current control, *H* is the magnet field strength.

From (3), (4), the boundary conditions on loaded surfaces, the strains along the axes the system of equations for the generalized structural-parametric model and the generalized parametric structural schematic diagram Figure 1 of the actuator are determined

$$\Xi_1(p) = \left(\frac{1}{M_1 p^2}\right)\left\{-F_1(p) + \left(\frac{1}{\chi_{ij}^{\Psi}}\right)\left[\begin{matrix} d_{mi}\Psi_m(p) - \\ \left(\dfrac{\gamma}{\operatorname{sh}(l\gamma)}\right)\left[\operatorname{ch}(l\gamma)\Xi_1(p) - \Xi_2(p)\right]\end{matrix}\right]\right\}$$

$$(6)$$

$$\Xi_2(p) = \left(\frac{1}{M_2 p^2}\right)\left\{-F_2(p) + \left(\frac{1}{\chi_{ij}^{\Psi}}\right)\left[\begin{matrix} d_{mi}\Psi_m(p) - \\ \left(\dfrac{\gamma}{\operatorname{sh}(l\gamma)}\right)\left[\operatorname{ch}(l\gamma)\Xi_2(p) - \Xi_1(p)\right]\end{matrix}\right]\right\}$$

Where $\chi_{ij}^{\Psi} = \dfrac{s_{ij}^{\Psi}}{S_0}$ $d_{mi} = \begin{cases} d_{33}, d_{31}, d_{15} \\ g_{33}, g_{31}, g_{15} \\ d_{33}, d_{31}, d_{15} \end{cases}$, $\Psi_m = \begin{cases} E_3, E_3, E_1 \\ D_3, D_3, D_1 \\ H_3, H_3, H_1 \end{cases}$,

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

$\gamma^{\Psi} = \{\gamma^{E}, \gamma^{D}, \gamma^{H}$, d_{mi} is the coefficient of the electromagnetolasticity (for example the piezomodule or the coefficient of the magnetostriction).

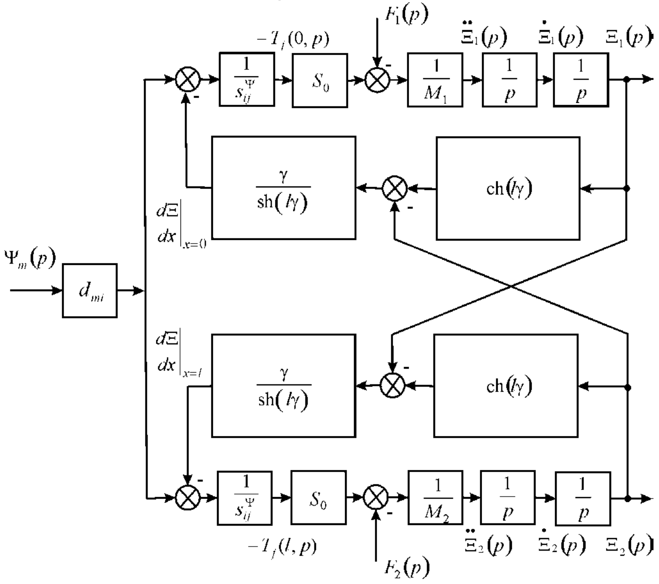

Figure 1: Generalized parametric structural schematic diagram of the electromagnetoelastic actuator

The generalized transfer functions of the electromagnetoelastic actuator are the ratio of the Laplace transform of the displacement of the face actuator and the Laplace transform of the corresponding control parameter or the force at zero initial conditions.

III. Matrix Transfer Function

The matrix transfer function of the electromagnetoelastic actuator for the nanomedicine and the nanotechnology is deduced from its structural-parametric model (6) in the following form

$$\begin{pmatrix} \Xi_1(p) \\ \Xi_2(p) \end{pmatrix} = \begin{pmatrix} W_{11}(p) & W_{12}(p) & W_{13}(p) \\ W_{21}(p) & W_{22}(p) & W_{23}(p) \end{pmatrix} \begin{pmatrix} \Psi_m(p) \\ F_1(p) \\ F_2(p) \end{pmatrix} \quad (7)$$

For $m << M_1$ and $m << M_2$ the static displacement of the faces of the piezoactuator for the transverse piezo effect are obtained

$$\xi_1(\infty) = \lim_{\substack{p \to 0 \\ \alpha \to 0}} \frac{pW_{11}(p)U_0}{\delta p} = \frac{d_{31}hU_0M_2}{\delta(M_1+M_2)} \quad (8)$$

$$\xi_2(\infty) = \lim_{\substack{p \to 0 \\ \alpha \to 0}} \frac{pW_{21}(p)U_0}{\delta p} = \frac{d_{31}hU_0M_1}{\delta(M_1+M_2)} \quad (9)$$

For the piezoactuator from PZT under the transverse piezoeffect at $m << M_1$, $m << M_2$, $d_{31} = 2.5 \cdot 10^{-10}$ m/V, $h/\delta = 20$, $U = 30$ V, $M_1 = 2$ kg, $M_2 = 8$ kg the static displacements of the faces are determined $\xi_1(\infty) = 120$ nm, $\xi_2(\infty) = 30$ nm, $\xi_1(\infty) + \xi_2(\infty) = 150$ nm.

For the approximation of the hyperbolic cotangent by two terms of the power series in transfer function (7) the following expressions of the transfer function of the piezoactuator is obtained for the elastic-inertial load at $M_1 \to \infty$, $m << M_2$ under the transverse piezoeffect

$$W(p) = \frac{\Xi_2(p)}{U(p)} = \frac{d_{31}\, h/\delta}{\left(1 + C_e/C_{11}^E\right)(T_t^2 p^2 + 2T_t\xi_t p + 1)}$$

$$T_t = \sqrt{M_2/\left(C_e + C_{11}^E\right)}, \; \xi_t = \alpha h^2 C_{11}^E \Big/ \left(3c^E \sqrt{M\left(C_e + C_{11}^E\right)}\right) \quad (10)$$

where $U(p)$ is the Laplace transform of the voltage, T_t is the time constant and ξ_t is the damping coefficient of the piezoactuator. The expression for the transient response of the voltage-controlled piezoactuator for the elastic-inertial load is determined

$$\xi(t) = \xi_m \left(1 - \frac{e^{-\frac{\xi_t t}{T_t}}}{\sqrt{1-\xi_t^2}} \sin(\omega_t t + \varphi_t) \right) \quad (11)$$

$$\xi_m = \frac{d_{31}(h/\delta)U_m}{1 + C_e/C_{11}^E}, \; \omega_t = \frac{\sqrt{1-\xi_t^2}}{T_t}, \; \varphi_t = \operatorname{arctg}\left(\frac{\sqrt{1-\xi_t^2}}{\xi_t}\right)$$

Where ξ_m the steady-state value of displacement of the piezoactuator is, U_m is the amplitude of the voltage. For the voltage-controlled piezoactuator from the piezoceramics PZT under the transverse piezoelectric effect for the elastic-inertial load $M_1 \to \infty$, $m << M_2$ and input voltage with amplitude $U_m = 25$ V at $d_{31} = 2.5 \cdot 10^{-10}$ m/V, $h/\delta = 20$, $M_2 = 4$ kg, $C_{11}^E = 2 \cdot 10^7$ N/m, $C_e = 0.5 \cdot 10^7$ H/m are obtained values $\xi_m = 100$ nm, $T_t = 0.4 \cdot 10^{-3}$ c. The characteristics of the piezoactuator are described with using its physical parameters and external load.

IV. Results and Discussions

The structural-parametric model and parametric structural schematic diagrams of the voltage-controlled piezoactuator for the longitudinal, transverse and shift piezoeffects are determined from the generalized structural-parametric model of the electro-magnetoelastic actuator with the replacement of the following parameters.

$$\Psi_m = \{E_3, E_3, E_1 \, , \; d_{mi} = \{d_{33}, d_{31}, d_{15} \, , \; s_{ij}^{\Psi} = \{s_{33}^E, s_{11}^E, s_{55}^E \, , \; l = \{\delta, h, b$$

The generalized structural-parametric model, the generalized parametric structural schematic diagram and the matrix transfer function of the electro-magnetoelastic actuator are obtained from the solutions of the equation of the electromagnetoelasticity, the Laplace transform and the linear ordinary differential equation of the second order.

From the generalized matrix transfer function of the electromagnetoelastic actuator after algebraic transformations are constructed the matrix transfer function of the piezoactuator for the longitudinal, transverse and shift piezoeffects.

V. Conclusions

The generalized structural-parametric model, the generalized parametric structural schematic diagram, the matrix transfer function of the electromagnetoelastic actuator for the nanomechanics are obtained.

The structural-parametric model, the matrix transfer function and the parametric structural schematic diagram of the piezoactuator for the transverse, longitudinal, shift piezoeffects are obtained from the generalized structural-parametric model of the electro-magnetoelastic actuator. From the solution of the equation of the electromagnetolasticity, the wave equation with the Laplace transform and the deformations along the axes the generalized structural-parametric model and the generalized parametric structural schematic diagram of the electro-magnetoelastic actuator are constructed for the control systems in the nanomechanics. The deformations of the actuator are described by using the matrix transfer function of the electromagnetoelastic actuator.

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