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Electro Magneto Elastic Actuator for Nanomedicine and Nanotechnology

Afonin SM*

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

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***Corresponding author:** SM Afonin, Department of Intellectual Technical Systems, National Research University of Electronic Technology MIET, 124498, Moscow, Russia, Email : learner01@mail.ru

Abstract

From the structural-parametric model of the electromagnetoelastic actuator we obtain the parametric structural schematic diagram and the matrix transfer function, the characteristics of the electromagnetoelastic actuator for the nanomedicine and the nanotechnology. The generalized parametric structural schematic diagram, the matrix transfer function of the electromagnetoelastic actuator are described with using its physical parameters and external load.

Keywords: Electromagnetoelastic actuator; Nano displacement; Piezo actuator; Parametric structural schematic diagram; Matrix transfer function

Introduction

The electromagnetoelastic actuator for piezoelectric, piezomagnetic, electrostriction, magnetostriction effects is used for the precise adjustment in the nanomedicine, the nanotechnology and the adaptive optics [1-32]. The piezo actuator on the inverse piezo effect is serves for the actuation of mechanisms or the management, converts the electrical signals into the displacement and the force [1-8]. The piezo actuator for the nanomedicine is provided the displacement from nano meters to tens of micrometres, a force to 1000 N. The piezo actuator is used for research in the nanomedicine and the nanotechnology for the scanning tunnelling microscopes, scanning force microscopes and atomic force microscopes [14-32].

In the present paper the generalized structural-parametric model and the generalized parametric structural schematic diagram of the electromagneto elastic actuator are constructed by solving the wave equation with the Laplace transform for the equation of the electromagnetolasticity, 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 piezo actuator are obtained from the generalized structural-parametric model. In [6,7] was determined the solution of the wave equation of the piezo actuator. In the [14-16,30] were obtained the structural-parametric models, the schematic diagrams for simple piezo actuator and this model were transformed to the structural-parametric model of the electromagnetoelastic actuator. The structural-parametric model of the electro elastic 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 piezo actuator 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 piezo actuator 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 piezo actuator 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 the equation of electro magnetoelasticity.

Structural-Parametric Model

The general structural-parametric model and the parametric structural schematic diagram of the electromagnetoelastic actuator are obtained. In the electro elastic 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 electro elastic actuator its deformation corresponds to stressed state. For polarized 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

$$\mathbf{D} = \mathbf{dT} + \boldsymbol{\varepsilon}^T \mathbf{E} \quad (1)$$

$$\mathbf{S} = \mathbf{s}^E \mathbf{T} + \mathbf{d}^t \mathbf{E} \quad (2)$$

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 piezo actuator (piezo plate) has the following properties: δ is the thickness, h is the height, b is the width, respectively $l = \{\delta, h, b$ the length of the piezo actuator for the longitudinal, transverse and shift piezo effects. 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 piezo effect for controlling voltage [6, 12] has the form

$$S_i = d_{mi}\Psi_m(t) + s_{ij}^{\Psi} T_j(x,t) \quad (3)$$

$$S_i = \partial\xi(x,t)/\partial x\,,\ \Psi_m(t) = E_m(t) = U(t)/\delta$$

where S_i is the relative displacement of the cross section of the piezo actuator along axis *i*, $\Psi_m(t)$ is the control parameter along axis *m*, d_{mi} is the piezo module, $E_m(t)$ 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 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 piezo actuator is respectively, the thickness, the height, the width for the longitudinal, transverse, shift piezo effects.

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

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

with its solution

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

where $\Xi(x,p)$ is the Laplace transform of the displacement of the section of the piezo actuator, $\gamma = p/c^{\Psi} + \alpha$ 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 (3,5), 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

$$\Xi_1(p) = \left(\frac{1}{M_1 p^2}\right)\left\{-F_1(p) + \left(\frac{1}{\chi_{ij}^{\Psi}}\right)\left[\begin{matrix} d_{mi}\Psi_m(p) - \\ \left(\frac{\gamma}{\operatorname{sh}(l\gamma)}\right)\left[\operatorname{ch}(l\gamma)\Xi_1(p) - \Xi_2(p)\right]\end{matrix}\right]\right\} \quad (6)$$

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

where

$$\chi_{ij}^{\Psi} = \frac{s_{ij}^{\Psi}}{S_0},\ d_{mi} = \begin{cases} d_{33}, d_{31}, d_{15} \\ g_{33}, g_{31}, g_{15} \\ d_{33}, d_{31}, d_{15} \end{cases},\ \Psi_m = \begin{cases} E_3, E_3, E_1 \\ D_3, D_3, D_1 \\ H_3, H_3, H_1 \end{cases},\ l = \{\delta, h, b,\ c^{\Psi} = \{c^E, c^D, c^H,$$

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

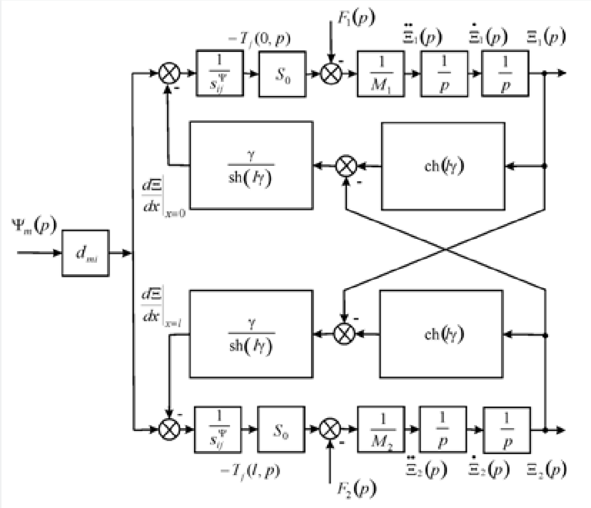

Figure 1: Generalized parametric structural schematic diagram of the electromagnetoelastic actuator.

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.

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 piezo actuator 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 piezo actuator from PZT under the transverse piezo effect at $m{<<}M_1$ and $m{<<}M_2$, $d_{13} = 2.5*10^{-10}$ m/V, $h/\delta = 20$, *U*=60V,

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M_1=10kg and M_2=40kg the static displacement of the faces are determined $\xi_1(\infty)=240\,\mathrm{nm}$, $\xi_2(\infty)=60\,\mathrm{nm}$, $\xi_1(\infty)+\xi_2(\infty)=300\,\mathrm{nm}$..

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 piezo actuator is obtained for the elastic-inertial load at $M_1 \to \infty$, $m < M_2$ under the transverse piezo effect

$$W(p)=\frac{\Xi_2(p)}{U(p)}=\frac{d_{31}\,h/\delta}{\left(1+C_e/C_{11}^E\right)\,(T_t^2p^2+2T_t\xi_tp+1)} \quad (10)$$

$$T_t=\sqrt{M_2/\left(C_e+C_1^E\right)},\ \xi_t=\alpha h^2C_1^E\Big/\left(3c^E\sqrt{M\left(C_e+C_1^E\right)}\right)$$

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 piezo actuator. The expression for the transient response of the voltage-controlled piezo actuator for the elastic-inertial load is determined

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

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

For the voltage-controlled piezo actuator from the piezoceramics PZT under the transverse piezoelectric effect for the elastic-inertial load, $M_1 \to \infty$, $\mathrm{m} << \mathrm{M}_2$ and input voltage with amplitude $U_m = 50\ \mathrm{V}$ at $d_{31}=2.5*10^{-10}\ \mathrm{m/V}$, $\mathrm{h}/\delta=20$, $M_2=9Kg$, $\mathrm{C}_{11}^E=\ 2*10^7\ \mathrm{N/m}$, $C_e=0.5*10^7$ N/m are obtained values $\xi_m=200\ \mathrm{nm}$, $\mathrm{T}_t=0.6*10^{-3}S$

Results and Discussions

The structural-parametric model and parametric structural schematic diagrams of the voltage-controlled piezo actuator for the longitudinal, transverse and shift piezo effects are determined from the generalized structural-parametric model of the electromagnetoelastic actuator with the replacement of the following parameters.

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

The generalized structural-parametric model, the generalizedparametric structural schematic diagram and the matrix equation of the electromagnetoelastic 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 equation for the transfer functions of the electromagnetoelastic actuator after algebraic transformations are constructed the matrix equations of the piezo actuator for the longitudinal, transverse and shift piezo effects.

Conclusion

The generalized structural-parametric model, the generalized parametric structural schematic diagram, the matrix equation of the electromagnetoelastic actuator for the nanomedicine and the nanotechnology are obtained.

The structural-parametric model, the matrix equation and the parametric structural schematic diagram of the piezo actuator for the transverse, longitudinal, shift piezo effects are obtained from the generalized structural-parametric model of the electromagnetoelastic actuator. From the solution of the wave equation with the Laplace transform, from the equation of the electromagnetolasticity and the deformations along the coordinate axes the generalized structural-parametric model and the generalized parametric structural schematic diagram of the electromagnetoelastic actuator are constructed for the control systems in the nanomedicine and the nanotechnology. The deformations of the actuator are described by the matrix transfer function of the actuator.

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