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Structural-Parametric Model Multilayer Electromagnetoelastic Actuator for Nanomechatronics

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Abstract In this work, the structural-parametric model and the parametric structural schematic diagram of the multilayer electromagnetoelastic actuator for nanomechatronics are received. The purpose of the research is to obtain structural-parametric model of the multilayer electromagnetoelastic actuator for the nanomechatronics systems. The method of mathematical physics is used to solve the matrix equation of the multilayer electromagnetoelastic actuator for its structural-parametric model. The generalized parametric structural schematic diagrams of the multilayer electromagnetoelastic actuator or the multilayer piezoactuator for nanomechatronics with the mechanical parameters the displacement and the force are determined in contrast to Cady and Mason's electrical equivalent circuits for the calculation of the piezotransmitter, the piezoreceiver, the vibration piezomotor. We obtain the generalized structural-parametric model and the generalized parametric structural schematic diagram of the multilayer electromagnetoelastic actuator from the general equation of the electromagnetoelasticity and determination of the caused force, the system of the equations for the equivalent quadripole of the multilayer actuator, the equations of the forces on its faces. The decision matrix equation for the equivalent quadripole of the multilayer electromagnetoelastic actuator is used. The parametric structural schematic diagram of multilayer electromagnetoelastic actuator is obtained with the mechanical parameters the displacement and the force. The matrix transfer function of the multilayer electromagnetoelastic actuator is determined for nanomechatronics. The generalized parametric structural schematic diagram, the generalized matrix equation of the multilayer electromagnetoelastic actuator for nanomechatronics are obtained. The deformations of the multilayer electromagnetoelastic actuator for nanomechatronics are described by the matrix equation. The parametric structural schematic diagram and the matrix transfer function of the multilayer piezoactuator are obtained for calculations the nanomechatronics systems with the multilayer piezoactuator of micro and nanodisplacement.

Keywords: *multilayer electromagnetoelastic actuator, multilayer piezoactuator, piezolayer, structural-parametric model, equivalent quadripole, parametric structural schematic diagram, matrix transfer function*

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1. Introduction

The multilayer electromagnetoelastic actuator on the piezoelectric, piezomagnetic, electrostriction, magnetostriction effects is used for precise alignment in the range of movement from nanometers to tens of micrometers for the nanomechatronics systems in nanotechnology, nanobiology and adaptive optics [1-8].

The parametric structural schematic diagrams of the multilayer piezoactuator are determined in contrast to Cady and Mason's electrical equivalent circuits for the calculation of the piezotransmitter, the piezoreceiver, the vibration piezomotor [1-12]. The parametric structural schematic diagram of the multilayer electromagnetoelastic actuator is obtained with the mechanical parameters the displacement and the force.

The piezoactuator is the piezomechanical device intended for actuation of the mechanisms, the systems or the management, based on the piezoeffect, converts the electrical signals into mechanical movement or the force [14-20].

The investigation of the static and dynamic characteristics of the multilayer piezoactuator is necessary for the calculation the nanomechatronics systems. The multilayer piezoactuators are used in nanotechnology for the scanning tunneling microscope and the atomic force microscope [6-35].

2. Structural-parametric Model and Schematic Diagram

In this work, the parametric structural schematic diagram and the matrix transfer function of the multilayer electromagnetoelastic actuator on Figure 1 for the nanomechatronics are obtained from the structural-parametric model of the multilayer actuator with the mechanical parameters the displacement and the force. In the general case, the equation of the electromagnetoelasticity of the multilayer electromagnetoelastic actuator [12,14,31] has the form

$$S_i = \nu_{mi}\Psi_m(t) + s_{ij}^{\Psi}T_j(x,t), \qquad (1)$$

where $S_i = \partial\xi(x,t)/\partial x$ is the relative displacement along axis i of the cross section of the actuator, $\Psi = E, D, H$ is the generalized control parameter in the form E_m for the voltage control, D_m for the current control, H_m for the magnetic field strength control along axis m, T_j is the mechanical stress along axis j, ν_{mi} is the coefficient of electromagnetoelasticity, for example, this coefficient is d_{mi} piezomodule or magnetostriction coefficient, s_{ij}^{Ψ} is the elastic compliance with $\Psi = \text{const}$, the indexes are i = 1, 2, … , 6, j = 1, 2, … , 6, m = 1, 2, 3 and 1, 2, 3 are perpendicular coordinate axes.

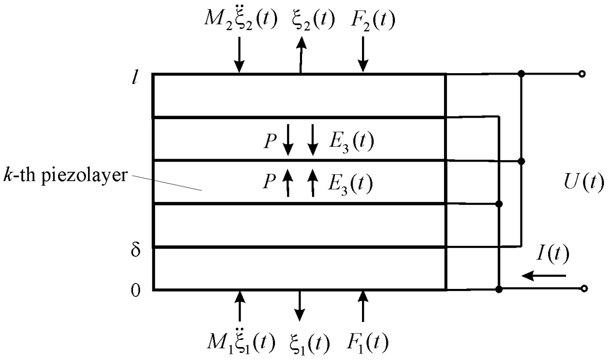

Figure 1. Multilayer piezoactuator for longitudinal piezoeffect

The multilayer piezoactuator on Figure 1 consist from the piezolayers or the piezoplates, connected electrically in parallel and mechanically in series.

In this work we consider the matrix equation for the Laplace transforms of the forces and of the displacements [20] at the input and output faces of k-th piezolayer of the multilayer piezoactuator from n layers. The equivalent T-shaped quadripole of k-th piezolayer is shown on Figure 2.

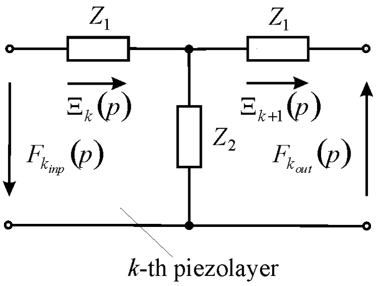

Figure 2. The quadripole for k-th piezolayer

The circuit of the multilayer piezoactuator on Fugure 2 is the equivalent T-shaped quadripole for k-th piezolayer and the forces equations, acting on the faces the piezolayer. We have the Laplace transforms of the forces for the input and output faces of k-th piezolayer on Fugure 2 in the form of the system of the equations for the equivalent T-shaped quadripole

$$\begin{aligned} F_{k_{inp}}(p) &= -(Z_1+Z_2)\Xi_k(p) + Z_2\Xi_{k+1}(p), \\ -F_{k_{out}}(p) &= -Z_2\Xi_k(p) + (Z_1+Z_2)\Xi_{k+1}(p) \end{aligned} \qquad (2)$$

where $Z_1 = \dfrac{S_0\gamma\,\text{th}(\delta\gamma)}{s_{ij}^{\Psi}}$. $Z_2 = \dfrac{S_0\gamma}{s_{ij}^{\Psi}\,\text{sh}(\delta\gamma)}$ are the resistance of the equivalent quadripole of k-th piezolayer, δ is the thickness, $\gamma = s/c^{\Psi} + \alpha$ is the coefficient of wave propagation, $F_{k_{inp}}(p)$. $F_{k_{out}}(p)$ are the Laplace transform of the forces at the input and output faces of k-th piezolayer, $\Xi_k(p)$, $\Xi_{k+1}(p)$ are the Laplace transforms of the displacements at input and output faces of k-th piezolayer, s is the Laplace operator, c^{Ψ} is the speed of the sound in the piezoceramics with $\Psi = \text{const}$, α is the attenuation coefficient, s_{ij}^{Ψ} is the elastic compliance with $\Psi = \text{const}$.

Therefore, we have the Laplace transforms the system of the equations for k-th piezolayer on Figure 2 in the form

$$\begin{aligned} -F_{k_{inp}}(p) &= \left(1+\frac{Z_1}{Z_2}\right)F_{k_{out}}(p) \\ &\quad + Z_1\left(2+\frac{Z_1}{Z_2}\right)\Xi_{k+1}(p), \end{aligned} \qquad (3)$$

$$\Xi_k(p) = \frac{1}{Z_1}F_{k_{out}}(p) + \left(1+\frac{Z_1}{Z_2}\right)\Xi_{k+1}(p).$$

Respectively, the matrix equation for k-th piezolayer has the following form

$$\begin{bmatrix} -F_{k_{inp}}(p) \\ \Xi_k(p) \end{bmatrix} = [M]\begin{bmatrix} F_{k_{out}}(p) \\ \Xi_{k+1}(p) \end{bmatrix}, \qquad (4)$$

the matrix $[M]$ has the form

$$[M] = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} 1+\dfrac{Z_1}{Z_2} & Z_1\left(2+\dfrac{Z_1}{Z_1}\right) \\ \dfrac{1}{Z_2} & 1+\dfrac{Z_1}{Z_2} \end{bmatrix}, \qquad (5)$$

where

$$m_{11} = m_{22} = 1+\frac{Z_1}{Z_2} = \text{ch}(\delta\gamma),$$

$$m_{12} = Z_1\left(2+\frac{Z_1}{Z_1}\right) = Z_0\text{sh}(\delta\gamma),$$

$$m_{21} = \frac{1}{Z_2} = \frac{\text{sh}(\delta\gamma)}{Z_0},\ Z_0 = \frac{S_0\gamma}{s_{ij}^{\Psi}}.$$

For the multilayer piezoactuator of the Laplace transform the displacement $\Xi_{k+1}(p)$ and the force $F_{k_{out}}(p)$ acting on the output face of k-th layer are corresponded to Laplace transforms of displacement and force acting on the input face of (k + 1)-th layer.

The force on the output face for *k*-th piezolayer is equal in magnitude and opposite in direction to the force on the input face for (*k* + 1)-th piezolayer

$$F_{k_{out}}(p)=-F_{k+1_{inp}}(p). \tag{6}$$

From (4) the matrix equation for *n* piezolayers has the form

$$\begin{bmatrix}-F_{1_{inp}}(p)\\ \Xi_1(p)\end{bmatrix}=[M]^n\begin{bmatrix}F_{n_{out}}(p)\\ \Xi_{n+1}(p)\end{bmatrix}, \tag{7}$$

where the matrix of the multilayer piezoactuator

$$[M]^n=\begin{bmatrix}\mathrm{ch}(n\delta\gamma) & Z_0\mathrm{sh}(n\delta\gamma)\\ \dfrac{\mathrm{sh}(n\delta\gamma)}{Z_0} & \mathrm{ch}(n\delta\gamma)\end{bmatrix}. \tag{8}$$

The equivalent quadripole of the multilayer piezoactuator similar Figure 2 and the matrix of the multilayer piezoactuator has the form

$$[M]^n=\begin{bmatrix}\mathrm{ch}(l\gamma) & Z_0\mathrm{sh}(l\gamma)\\ \dfrac{\mathrm{sh}(l\gamma)}{Z_0} & \mathrm{ch}(l\gamma)\end{bmatrix}, \tag{9}$$

where $l=n\delta$ is the length of the multilayer piezoactuator for the longitudinal piezoeffect, δ is the thickness for *k*-th piezolayer.

Equations of the forces, acting on the faces of the multilayer piezoactuator, have the following form

$$\begin{aligned}&\text{at } x=0, T_j(0,p)S_0=F_1(p)+M_1p^2\Xi_1(p),\\ &\text{at } x=l, T_j(l,s)S_0=-F_2(p)-M_2p^2\Xi_2(p),\end{aligned} \tag{10}$$

where $T_j(0,p)$, $T_j(l,p)$ are the Laplace transforms of mechanical stresses at the two ends of the multilayer piezoactuator.

Respectively, the Laplace transforms of the displacement and the force for the first face of the multilayer piezoactuator on Figure 1 have the form at $x=0$ and $\Xi_1(p)$, $F_1(p)$, the Laplace transforms of the displacement and the forces for the second face of the piezoactuator have the form at $x=l$ and

$$\Xi_2(p)=\Xi_{n+1}(p), F_2(p)=F_{n_{out}}(p).$$

Let us construct the structural-parametric model of the multilayer piezoactuator at the longitudinal piezoeffect. From equation (1) the Laplace transform the caused force, which causes the deformation, has the form

$$F(p)=d_{33}S_0E_3(p)/s_{33}^E, \tag{11}$$

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

Therefore, the structural-parametric model and the parametric structural schematic diagram of the multilayer piezoactuator at the longitudinal piezoeffect on Figure 3 have the following form

$$\Xi_1(p)=\left[\frac{1}{M_1p^2}\right]\left\{\begin{array}{l}-F_1(p)+\left(\dfrac{1}{\chi_{33}^E}\right)\\ \times\left[d_{33}E_3(p)-\left[\dfrac{\gamma}{\mathrm{sh}(l\gamma)}\right]\times\left[\mathrm{ch}(l\gamma)\Xi_1(p)-\Xi_2(p)\right]\right]\end{array}\right\}$$

$$\Xi_2(p)=\left[\frac{1}{M_2p^2}\right]\left\{\begin{array}{l}-F_2(p)+\left(\dfrac{1}{\chi_{33}^E}\right)\\ \times\left[d_{33}E_3(p)-\left[\dfrac{\gamma}{\mathrm{sh}(l\gamma)}\right]\times\left[\mathrm{ch}(l\gamma)\Xi_2(p)-\Xi_1(p)\right]\right]\end{array}\right\} \tag{12}$$

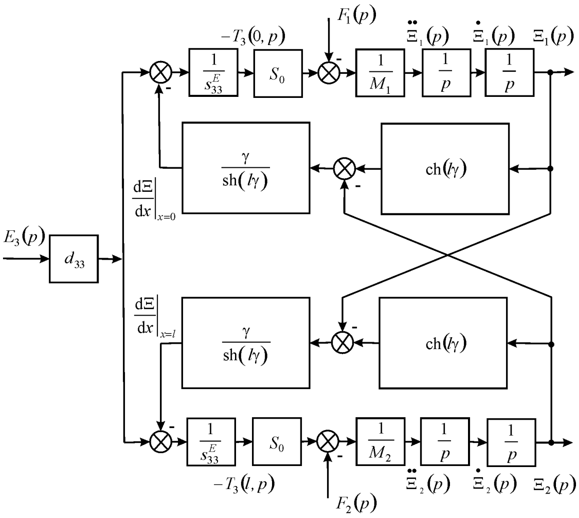

Figure 3. Parametric structural schematic diagram of voltage-controlled multilayer piezoactuator for longitudinal piezoeffect

Therefore, for the multilayer piezoactuator at the transverse piezoeffect от Figure 4 the Laplace transform the caused force has the form

$$F(p)=d_{31}S_0E_3(p)/s_{11}^E, \chi_{11}^E=s_{11}^E/S_0 \tag{13}$$

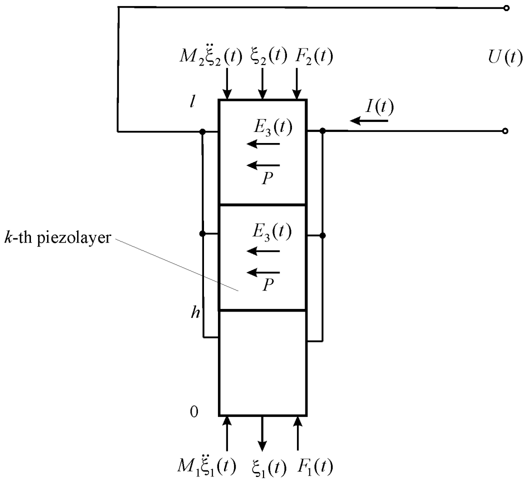

Figure 4. Multilayer piezoactuator for transverse piezoeffect

The structural-parametric model and the parametric structural schematic diagram on Figure 5 of the multilayer piezoactuator for the transverse piezoeffect have the form

$$\Xi_1(p)=\left[\frac{1}{M_1p^2}\right]\left\{\begin{array}{l}-F_1(p)+\left(\dfrac{1}{\chi_{11}^E}\right)\\ \times\left[\begin{array}{l}d_{31}E_3(p)-\left[\dfrac{\gamma}{\operatorname{sh}(l\gamma)}\right]\times\\ \left[\operatorname{ch}(l\gamma)\Xi_1(p)-\Xi_2(p)\right]\end{array}\right]\end{array}\right\}$$
$$\Xi_2(p)=\left[\frac{1}{M_2p^2}\right]\left\{\begin{array}{l}-F_2(p)+\left(\dfrac{1}{\chi_{11}^E}\right)\\ \times\left[\begin{array}{l}d_{31}E_3(p)-\left[\dfrac{\gamma}{\operatorname{sh}(l\gamma)}\right]\times\\ \left[\operatorname{ch}(l\gamma)\Xi_2(p)-\Xi_1(p)\right]\end{array}\right]\end{array}\right\} \quad (14)$$

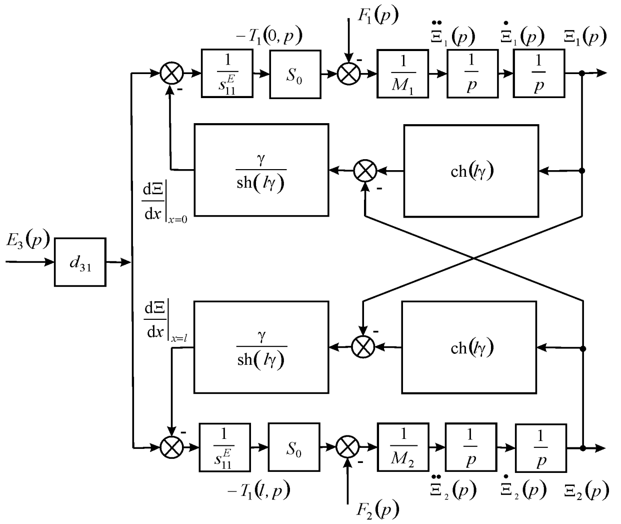

Figure 5. Parametric structural schematic diagram of voltage-controlled multilayer piezoactuator for transverse piezoeffect

For the multilayer piezoactuator at the shift piezoeffect on Figure 6 the Laplace transform the caused force has the form

$$F(p)=d_{15}S_0E_1(p)/s_{55}^E,\ \chi_{55}^E=s_{55}^E/S_0. \quad (15)$$

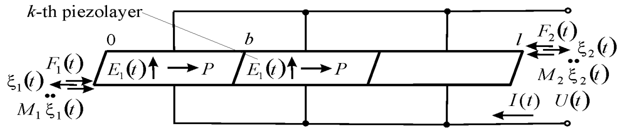

Figure 6. Multilayer piezoactuator for shift piezoeffect

The structural-parametric model and the structural diagram on Figure 7 of the multilayer piezoactuator for the shift piezoeffect have the form

$$\Xi_1(p)=\left[\frac{1}{M_1p^2}\right]\left\{\begin{array}{l}-F_1(p)+\left(\dfrac{1}{\chi_{55}^E}\right)\\ \times\left[\begin{array}{l}d_{15}E_1(p)-\left[\dfrac{\gamma}{\operatorname{sh}(l\gamma)}\right]\times\\ \left[\operatorname{ch}(l\gamma)\Xi_1(p)-\Xi_2(p)\right]\end{array}\right]\end{array}\right\}$$
$$\Xi_2(p)=\left[\frac{1}{M_2p^2}\right]\left\{\begin{array}{l}-F_2(p)+\left(\dfrac{1}{\chi_{55}^E}\right)\\ \times\left[\begin{array}{l}d_{15}E_1(p)-\left[\dfrac{\gamma}{\operatorname{sh}(l\gamma)}\right]\times\\ \left[\operatorname{ch}(l\gamma)\Xi_2(p)-\Xi_1(p)\right]\end{array}\right]\end{array}\right\} \quad (16)$$

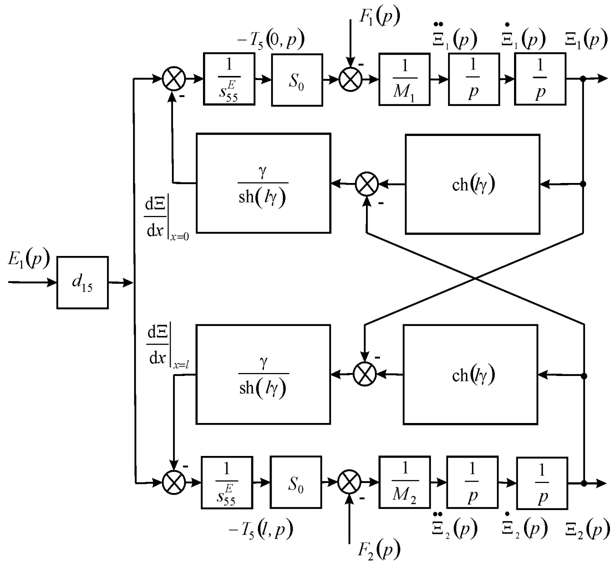

Figure 7. Parametric structural schematic diagram of voltage-controlled multilayer piezoactuator for shift piezoeffect

Let us construct the generalized structural-parametric model of the multilayer actuators on Figure 1, Figure 4, Figure 6. From equation (1) the Laplace transform the caused force has the form

$$F(p)=\nu_{mi}S_0\Psi_m(p)/s_{ij}^\Psi,\ \chi_{ij}^\Psi=s_{ij}^\Psi/S_0. \quad (17)$$

Therefore, we have the equations for the structural-parametric model and the generalized parametric structural schematic diagram of the multilayer electromagnetoelastic actuator on Figure 8. The structural-parametric model of the multilayer electromagnetoelastic actuator is obtained in result analysis of the equation of the caused force, of the system of the equations for the equivalent quadripole and the equations of the forces on its faces in the following form

$$\Xi_1(p)=\left[\frac{1}{M_1p^2}\right]\left\{\begin{array}{l}-F_1(p)+\left(\dfrac{1}{\chi_{ij}^\Psi}\right)\\ \times\left[\begin{array}{l}\nu_{mi}\Psi_m(p)-\left[\dfrac{\gamma}{\operatorname{sh}(l\gamma)}\right]\times\\ \left[\operatorname{ch}(l\gamma)\Xi_1(p)-\Xi_2(p)\right]\end{array}\right]\end{array}\right\}$$
$$\Xi_2(p)=\left[\frac{1}{M_2p^2}\right]\left\{\begin{array}{l}-F_2(p)+\left(\dfrac{1}{\chi_{ij}^\Psi}\right)\\ \times\left[\begin{array}{l}\nu_{mi}\Psi_m(p)-\left[\dfrac{\gamma}{\operatorname{sh}(l\gamma)}\right]\times\\ \left[\operatorname{ch}(l\gamma)\Xi_2(p)-\Xi_1(p)\right]\end{array}\right]\end{array}\right\} \quad (18)$$

where

$$\nu_{mi}=\begin{cases}d_{33},d_{31},d_{15}\\ g_{33},g_{31},g_{15}\\ d_{33},d_{31},d_{15}\end{cases},\ \Psi_m=\begin{cases}E_3,E_1\\ D_3,D_1\\ H_3,H_1\end{cases},\ s_{ij}^\Psi=\begin{cases}s_{33}^E,s_{11}^E,s_{55}^E\\ s_{33}^D,s_{11}^D,s_{55}^D\\ s_{33}^H,s_{11}^H,s_{55}^H\end{cases},$$

$$c^{\Psi}=\begin{cases}c^{E}\\ c^{D}\\ c^{H}\end{cases},\ \gamma=\begin{cases}\gamma^{E}\\ \gamma^{D}\\ \gamma^{H}\end{cases},\ l=\begin{cases}n\delta\\ nh\\ nb\end{cases}.$$

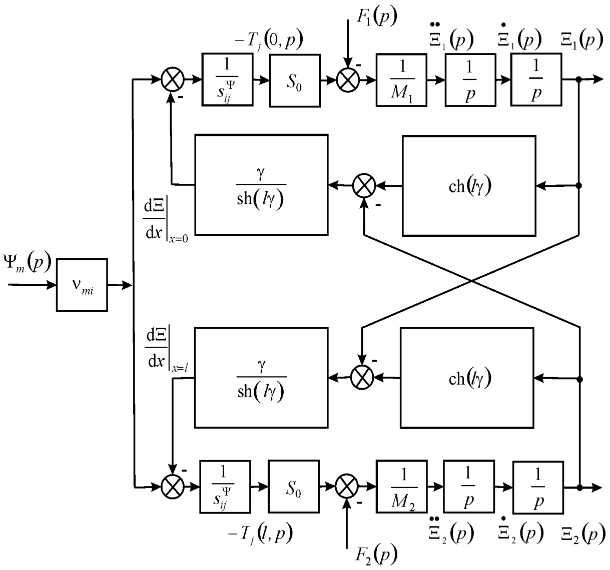

Figure 8. Generalized parametric structural schematic diagram of electromagnetoelastic actuator

We have for the multilayer piezoactuator on Figure 1, Figure 4, Figure 6 at the longitudinal piezoeffect the length of the multilayer piezoactuator in the form $l=n\delta$, at the transverse piezoeffect $l=nh$, at the shift piezoeffect $l=nb$, where δ,h,b are the thickness, the height, the width for k-th piezolayer.

The generalized parametric structural schematic diagram of the electromagnetoelastic actuator is constructed using the generalized structural-parametric model of the multilayer electromagnetoelastic actuator for nanomechatronics.

3. Matrix Transfer Function

We receive the matrix transfer function of the multilayer electromagnetoelastic actuator with n piezolayers from the system of the equations (18) in the following form

$$\begin{bmatrix}\Xi_1(p)\\ \Xi_2(p)\end{bmatrix}=\begin{bmatrix}W_{11}(p) & W_{12}(p) & W_{13}(p)\\ W_{21}(p) & W_{22}(p) & W_{23}(p)\end{bmatrix}\begin{bmatrix}\Psi_m(p)\\ F_1(p)\\ F_2(p)\end{bmatrix}. \quad (19)$$

In the general case, the matrix transfer function of the multilayer electromagnetoelastic actuator has the form

$$\left[\Xi(p)\right]=\left[W(p)\right]\left[P(p)\right], \quad (20)$$

$$\left[\Xi(p)\right]=\begin{bmatrix}\Xi_1(p)\\ \Xi_2(p)\end{bmatrix},$$

$$\left[W(p)\right]=\begin{bmatrix}W_{11}(p) & W_{12}(p) & W_{13}(p)\\ W_{21}(p) & W_{22}(p) & W_{23}(p)\end{bmatrix},$$

$$\left[P(p)\right]=\begin{bmatrix}\Psi_m(p)\\ F_1(p)\\ F_2(p)\end{bmatrix},$$

where $\left[\Xi(p)\right]$ is the matrix of the Laplace transforms of the displacements, $\left[W(p)\right]$ is the matrix transfer function, $\left[P(p)\right]$ the matrix of the Laplace transforms of the control parameter and the forces. The generalized transfer functions of the electromagnetoelastic actuator are the ratio of the Laplace transform of the displacement of the face and the Laplace transform of the corresponding control parameter or the force at zero initial conditions

$$W_{11}(p)=\Xi_1(p)/\Psi_m(p)=\nu_{mi}\left[M_2\chi_{ij}^{\Psi}p^2+\gamma\mathrm{th}(l\gamma/2)\right]/A_{ij},$$

$$A_{ij}=M_1M_2\left(\chi_{ij}^{\Psi}\right)^2p^4+\left\{\left(M_1+M_2\right)\chi_{ij}^{\Psi}/\left[c^{\Psi}\mathrm{th}(l\gamma)\right]\right\}p^3+\left[\left(M_1+M_2\right)\chi_{ij}^{\Psi}\alpha/\mathrm{th}(l\gamma)+1/\left(c^{\Psi}\right)^2\right]p^2+2\alpha p/c^{\Psi}+\alpha^2,$$

$$W_{21}(p)=\Xi_2(p)/\Psi_m(p)=\nu_{ij}\left[M_1\chi_{ij}^{\Psi}p^2+\gamma\mathrm{th}(l\gamma/2)\right]/A_{ij},$$

$$W_{12}(p)=\Xi_1(p)/F_1(p)=-\chi_{ij}^{\Psi}\left[M_2\chi_{ij}^{\Psi}p^2+\gamma/\mathrm{th}(l\gamma)\right]/A_{ij},$$

$$W_{13}(p)=\Xi_1(p)/F_2(p)=W_{22}(p)=\Xi_2(p)/F_1(p)=\left[\chi_{ij}^{\Psi}\gamma/\mathrm{sh}(l\gamma)\right]/A_{ij},$$

$$W_{23}(p)=\Xi_2(p)/F_2(p)=-\chi_{ij}^{\Psi}\left[M_1\chi_{ij}^{\Psi}p^2+\gamma/\mathrm{th}(l\gamma)\right]/A_{ij}.$$

From generalized structural-parametric model of the multilayer electromagnetoelastic actuator its generalized parametric structural schematic diagram and generalized matrix transfer function are determined to calculate the static and dynamic characteristics of the multilayer electromagnetoelastic actuator for the nanomechatronics.

For example, we receive for the voltage-controlled multilayer piezoactuator the static displacements of its faces at the transverse piezoeffect and the inertial load for $m<<M_1$, $m<<M_2$ and $F_1(t)=F_2(t)=0$ in the following form

$$\xi_1(\infty)=\lim_{t\to\infty}\xi_1(t)=\lim_{\substack{p\to 0\\ \alpha\to 0}}pW_{11}(p)\left(U_m/\delta\right)/p,$$

$$\xi_1(\infty)=d_{31}(l/\delta)U_m M_2/\left(M_1+M_2\right), \quad (21)$$

$$\xi_2(\infty)=\lim_{t\to\infty}\xi_2(t)=\lim_{\substack{p\to 0\\ \alpha\to 0}}pW_{21}(p)\left(U_m/\delta\right)/p,$$

$$\xi_2(\infty)=d_{31}(l/\delta)U_m M_1/\left(M_1+M_2\right), \quad (22)$$

$$\xi_1(\infty)+\xi_2(\infty)=d_{31}(l/\delta)U_m \quad (23)$$

where U_m is the amplitude of the voltage, m is the mass of the multilayer piezoactuator, M_1, M_2 are the load masses.

For the voltage-controlled multilayer piezoactuator from the piezoceramics PZT with the transverse piezoeffect for the inertial load at d_{31} = 2.5·10^{-10} m/V, l/δ = 20, U_m = 100 V, $M_1 = 1$ kg, $M_2 = 4$ kg, we obtain the static displacement of the faces of the multilayer piezoactuator $\xi_1(\infty)$ = 400 nm, $\xi_2(\infty)$ = 100 nm, $\xi_1(\infty)+\xi_2(\infty)$ = 500 nm.

We have for the voltage-controlled multilayer piezoactuator the static displacements of its faces at the longitudinal piezoeffect and the inertial load for $m << M_1$, $m << M_2$ and $F_1(t) = F_2(t) = 0$ in the form

$$\xi_1(\infty) = d_{33} n U_m M_2 \big/ (M_1 + M_2), \qquad (24)$$

$$\xi_2(\infty) = d_{33} n U_m M_1 \big/ (M_1 + M_2), \qquad (25)$$

$$\xi_1(\infty) + \xi_2(\infty) = d_{33} n U_m. \qquad (26)$$

For the voltage-controlled multilayer piezoactuator from the piezoceramics PZT under the longitudinal piezoeffect for the inertial load at d_{33} = 4·10^{-10} m/V, n = 16, U_m = 100 V, $M_1 = 1$ kg, $M_2 = 4$ kg, we obtain the static displacements of the faces of the multilayer piezoactuator $\xi_1(\infty)$ = 512 nm, $\xi_2(\infty)$ = 128 nm, $\xi_1(\infty)+\xi_2(\infty)$ = 640 nm.

From equation (20) at the elastic-inertial load and one fixed face for $M_1 \to \infty$, $m << M_2$, and the longitudinal piezoeffect with voltage control of the multilayer piezoactuator we receive the transfer function in the form

$$W(p) = \frac{\Xi_2(p)}{U(p)} = \frac{d_{33} n}{\left(1 + C_e \big/ C_{33}^E\right)\left(T_t^2 p^2 + 2T_t \xi_t p + 1\right)}, \quad (27)$$

$$T_t = \sqrt{M_2 \big/ \left(C_e + C_{33}^E\right)},$$

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

where $\Xi_2(p)$, $U(p)$ are the Laplace transforms the displacement face of the multilayer piezoactuator and the voltage, T_t is the time constant and ξ_t is the damping coefficient of the multilayer piezoactuator, $C_{33}^E = S_0 \big/ \left(s_{33}^E l\right)$ is the is rigidity of the multilayer piezoactuator at the longitudinal piezoeffect for $E = \text{const}$.

Therefore, in the static mode we obtain the equation for static displacement of the multilayer piezoactuator at the longitudinal piezoeffect and elastic load in the following form

$$\xi_m = \frac{d_{33} n U_m}{1 + C_e \big/ C_{33}^E}, \qquad (28)$$

where ξ_m is the steady-state value of displacement of the multilayer piezoactuator and U_m is the amplitude of the voltage.

From equation (27) the expression for the transient response of the voltage-controlled the multilayer piezoactuator at the longitudinal piezoeffect has the form

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

$$\omega_t = \sqrt{1 - \xi_t^2} \Big/ T_t, \quad \phi_t = \text{arctg}\left(\sqrt{1 - \xi_t^2} \Big/ \xi_t\right).$$

For the voltage-controlled multilayer piezoactuator from the piezoceramics PZT for the longitudinal piezoeffect with one fixed face and elastic-inertial load at $M_1 \to \infty$, $m << M_2$, U_m = 120 V, d_{33} = 4·10^{-10} m/V, n = 10, M_2 = 4 kg, C_{33}^E = 6·10^7 N/m, C_e = 0.4·10^7 N/m, we receive values the steady-state value of displacement ξ_m = 450 nm, the time constant T_t = 0.25·10^{-3} s. The discrepancy between the experimental data and calculation results is 5%.

4. Results and Discussions

The solution of the matrix equation for the equivalent quadripole of the multilayer electromagnetoelastic actuator with the Laplace transform are used for the construction the parametric structural schematic diagram of the multilayer actuator.

We obtained the generalized structural-parametric model and the parametric structural schematic diagram of the multilayer electromagnetoelastic actuator as the result of the joint solution of the general equation of the electromagnetoelasticity and determination of the caused force, the matrix equation for the equivalent quadripole of the multilayer actuator with the Laplace transform, the boundary conditions on the two loaded faces,

The matrix transfer function and the parametric structural schematic diagram of the multilayer electromagnetoelastic actuator are obtained from the set of equations describing the structural parametric model of the multilayer actuator for nanomechatronics.

5. Conclusions

In this work, we received the generalized structural-parametric model and the generalized parametric structural schematic diagram of the multilayer electromagnetoelastic actuator from the general equation of the electromagnetoelasticity and determination of the caused force, the system of the equations for the equivalent quadripole of the multilayer actuator, the equations of the forces on its faces. We obtained the parametric structural schematic diagram and the matrix transfer function of the multilayer piezoactuator.

We constructed the generalized structural-parametric model and the generalized parametric structural schematic diagram of the multilayer electromagnetoelastic actuator for nanomechatronics with the mechanical parameters the displacement and the force.

We determined the parametric structural schematic diagram of the multilayer piezoactuator at the transverse, longitudinal, shift piezoelectric effects and the matrix transfer function of the multilayer electromagnetoelastic actuator for nanomechatronics.

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