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Multilayer Electro Magneto Elastic Actuator for Nanomechanics

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Abstract- In this paper, we consider the generalized structural diagram of the multilayer electro magneto elastic actuator or the multilayer piezo actuator for the nanomechanics in contrast to Cady and Mason's electrical equivalent circuits for the calculation of the piezo transmitter and receiver, the vibration piezo motor. From the solution of the general equation of the electro magneto elasticity, the matrix equation for the equivalent quadripole of the multilayer electro magneto elastic actuator, and its boundary conditions we receive the generalized structural-parametric model, the structural diagram and matrix transfer function of the multilayer actuator.

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Strictly as per the compliance and regulations of:

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Keywords: multilayer electro magneto elastic actuator, multilayer piezo actuator, equivalent quadripole, structural diagram, structural-parametric model, matrix transfer function.

I. Introduction

At present, we use the multilayer electro magneto elastic actuator on the piezoelectric, piezomagnetic, electrostriction, and magnetostriction effects for precise alignment in the range of movement from nanometers to tens of micrometers in nanomechanics systems for nanotechnology and adaptive optics. We receive the parametric structural schematic diagram of the multilayer piezo actuator for nanomechanics in contrast to Cady and Mason's electrical equivalent circuits for the calculation of the piezo transmitter, the piezo receiver, and the vibration piezo motor [1 – 12]. The parametric structural schematic diagram of the multilayer electro magneto elastic actuator is obtained with the mechanical parameters of displacement and force [14 − 20].The piezo actuator use for actuation of mechanisms, systems, or management based on the piezo effect, and convert electrical signals into mechanical movement or force. The investigation of the static and dynamic characteristics of the multilayer piezo actuator is necessary for the calculation of nanomechatronics systems. We apply multilayer piezo actuator in nanotechnology for scanning tunneling microscopy and atomic force microscopy [6 − 32].

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II. Parametric Structural Schematic Diagram

In this paper, we have the parametric structural schematic diagram and the matrix transfer function of the multilayer electro magneto elastic actuator for the nanomechanics from its the structural-parametric model. In general, the equation for the electro magneto elasticity of the multilayer electro magneto elastic actuator [12, 14, 16, 31] has the form

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

where $S_i = \partial\xi(x,t)/\partial x$ is the relative displacement along axis *i* of the cross-section of the actuator, therefore, we obtain $\Psi = E,D,H$ the generalized control parameter in the form E_m in Figure 1 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 electro magneto elasticity, for example, d_{mi} piezo module or magnetostriction coefficient, s_{ij}^{Ψ} is the elastic compliance with $\Psi = \text{const}$, and the indexes *i* = 1, 2, … , 6, *j* = 1, 2, … , 6, *m* = 1, 2, 3, with 1, 2, 3 are perpendicular coordinate axes.

The multilayer piezo actuator on Figure 1 consists from the piezo layers or the piezo plates connected electrically in parallel and mechanically in series.

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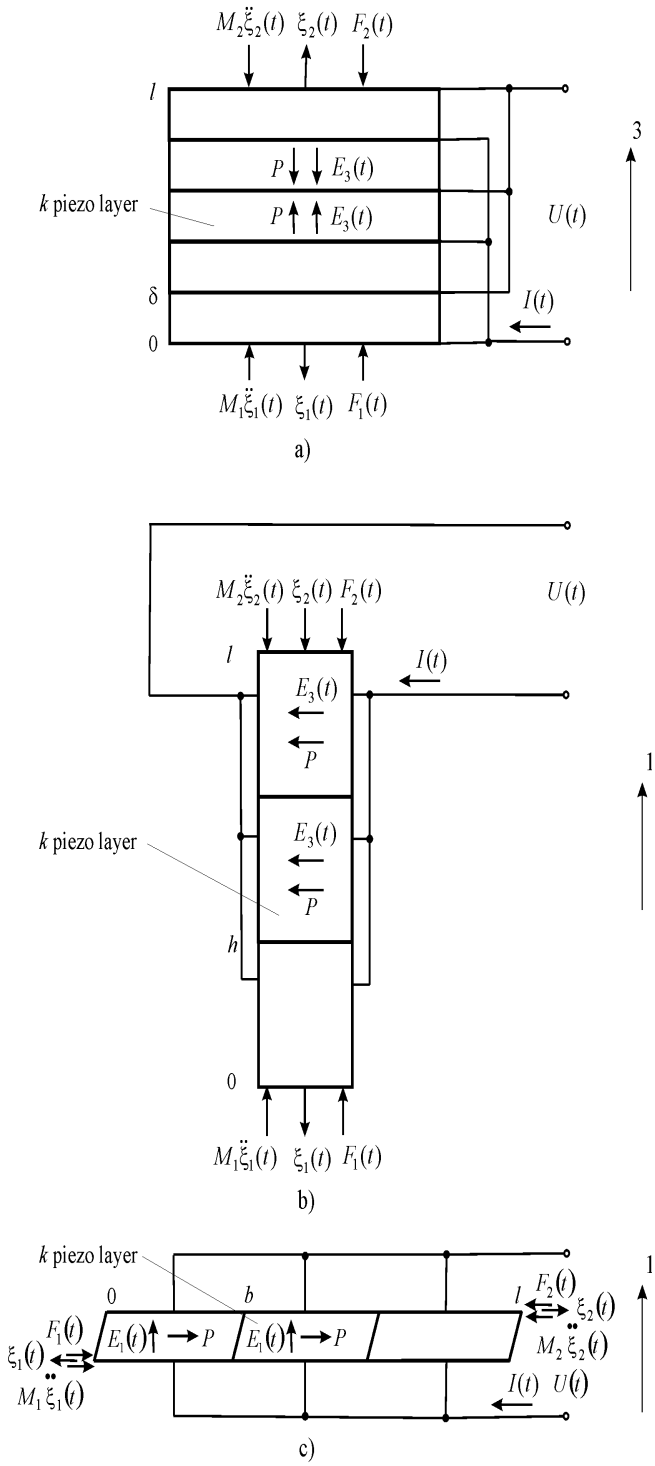

Figure 1: Multilayer piezo actuator a) for longitudinal piezo effect b) for transverse piezo effect, c) for shift piezo effect

For example, we consider the matrix equation for the Laplace transforms of the forces and the displacements [16] at the input and output ends of *k* the piezo layer of the multilayer piezo actuator from *n* the piezo layers. We drew the equivalent *T*-shaped quadripole of *k* the piezo layer in Figure 2.

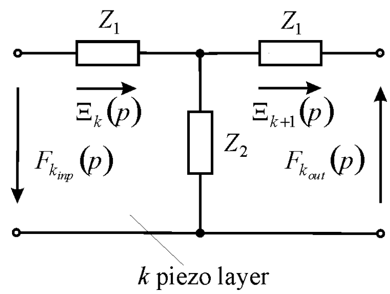

Figure 2: Quadripole for *k* piezo layer

The circuit of the multilayer piezo actuator on Figure 2 is compiled from the equivalent *T*-shaped quadripole for *k* the piezo layer and the forces equations, acting on the faces the piezo layer. Therefore, we have the Laplace transforms of the forces on the input and output faces of *k* the piezo layer of the multilayer piezo actuator in the form of the system of the equations for the equivalent *T*-shaped quadripole

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

where $Z_1 = \dfrac{S_0\gamma \operatorname{th}(\delta\gamma)}{s_{ij}^{\Psi}}$, $Z_2 = \dfrac{S_0\gamma}{s_{ij}^{\Psi}\operatorname{sh}(\delta\gamma)}$ are the resistance of the equivalent quadripole of *k* the piezo layer, δ is the thickness on Figure 1 a, $\gamma = \dfrac{p}{c^{\Psi}} + \alpha$, α are the coefficient of wave propagation and the coefficient of attenuation, *p* is the Laplace operator, c^{Ψ} is the speed of sound with $\Psi = \text{const}$, $F_{k_{inp}}(p)$, $F_{k_{out}}(p)$ are the Laplace transform of the forces at the input and output ends, $\Xi_k(p)$, $\Xi_{k+1}(p)$ are the Laplace transforms of the displacements at input and output ends of *k* the piezo layer in Figure 2.

Accordingly, we have for Figure 2 the Laplace transforms the following system of the equations for *k* the piezo layer in the form

$$-F_{k_{inp}}(p) = \left(1 + \frac{Z_1}{Z_2}\right)F_{k_{out}}(p) + Z_1\left(2 + \frac{Z_1}{Z_2}\right)\Xi_{k+1}(p)$$
$$\Xi_k(p) = \frac{1}{Z_1}F_{k_{out}}(p) + \left(1 + \frac{Z_1}{Z_2}\right)\Xi_{k+1}(p) \qquad (3)$$

the matrix equation for *k* the piezo layer

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

and the matrix $[M]$ in the form

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

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

$m_{12}=Z_1\left(2+\frac{Z_1}{Z_1}\right)=Z_0\mathrm{sh}(\delta\gamma)$, $m_{21}=\frac{1}{Z_2}=\frac{\mathrm{sh}(\delta\gamma)}{Z_0}$, $Z_0=\frac{S_0\gamma}{s_{ij}^{\Psi}}$

For the multilayer piezo actuator the Laplace transforms the displacement $\Xi_{k+1}(p)$ and the force $F_{k_{out}}(p)$ acting on the output face of k the piezo layer correspond the Laplace transforms of displacement and force acting on the input face of $k+1$ the piezo layer. The force on the output face for the k the piezo layer equal in magnitude and opposite in direction to the force on the input face for $k+1$ the piezo layer

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

From equation (3) the matrix equation for n the piezo layers

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

with the matrix of the multilayer piezo actuator Figure 1 a in the form

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

Accordingly, in general, the matrix for the equivalent quadripole of the multilayer electro magneto elastic actuator Figure 1 a-c has the following form

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

Therefore, we have from the equation (7) the equivalent quadripole of the multilayer piezo actuator on Figure 1 a-c for the longitudinal piezo effect with length of the multilayer piezo actuator $l=n\delta$, for the transverse piezo effect with $l=nh$, for the shift piezo effect with $l=nb$, where δ, h, b are the thickness, the height, the width for k the piezo layer.

Equations of the forces acting on the faces of the multilayer piezo actuator

$$\begin{aligned} &\text{at } x=0,\ T_j(0,p)S_0=F_1(p)+M_1p^2\Xi_1(p) \\ &\text{at } x=l,\ T_j(l,s)S_0=-F_2(p)-M_2p^2\Xi_2(p) \end{aligned} \tag{8}$$

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

The Laplace transform of the displacement and the force for the first face of the multilayer piezo actuator

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 piezo actuator

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 electro magneto elastic actuator Figure 1 a-c. From equation (1) the Laplace transform of the caused force, which causes the deformation, has the following form

$$\begin{aligned} &F(p)=\nu_{mi}S_0\Psi_m(p)/s_{ij}^{\Psi} \\ &\chi_{ij}^{\Psi}=s_{ij}^{\Psi}/S_0 \end{aligned} \tag{9}$$

Accordingly, we have the equations for the generalized structural-parametric model and the generalized parametric structural schematic diagram of the multilayer electro magneto elastic actuator on Figure 3. We receive the structural-parametric model in result analysis of the equation of the caused force and the system of the equations for the equivalent quadripole of the multilayer electro magneto elastic actuator, the forces on its faces in the following form

$$\begin{aligned} &\Xi_1(p)=\left[\frac{1}{M_1p^2}\right]\left\{-F_1(p)+\left(\frac{1}{\chi_{ij}^{\Psi}}\right)\left[\nu_{mi}\Psi_m(p)-\left[\frac{\gamma}{\mathrm{sh}(l\gamma)}\right]\times\left[\mathrm{ch}(l\gamma)\Xi_1(p)-\Xi_2(p)\right]\right]\right\} \\ &\Xi_2(p)=\left[\frac{1}{M_2p^2}\right]\left\{-F_2(p)+\left(\frac{1}{\chi_{ij}^{\Psi}}\right)\left[\nu_{mi}\Psi_m(p)-\left[\frac{\gamma}{\mathrm{sh}(l\gamma)}\right]\times\left[\mathrm{ch}(l\gamma)\Xi_2(p)-\Xi_1(p)\right]\right]\right\} \end{aligned} \tag{10}$$

where $\nu_{mi}=\begin{cases} d_{33},d_{31},d_{15} \\ g_{33},g_{31},g_{15} \\ d_{33},d_{31},d_{15} \end{cases}$, $\Psi_m=\begin{cases} E_3,E_1 \\ D_3,D_1 \\ H_3,H_1 \end{cases}$, $s_{ij}^{\Psi}=\begin{cases} s_{33}^E,s_{11}^E,s_{55}^E \\ s_{33}^D,s_{11}^D,s_{55}^D \\ s_{33}^H,s_{11}^H,s_{55}^H \end{cases}$ $c^{\Psi}=\begin{cases} c^E \\ c^D \\ c^H \end{cases}$, $\gamma=\begin{cases} \gamma^E \\ \gamma^D \\ \gamma^H \end{cases}$, $l=\begin{cases} n\delta \\ nh \\ nb \end{cases}$.

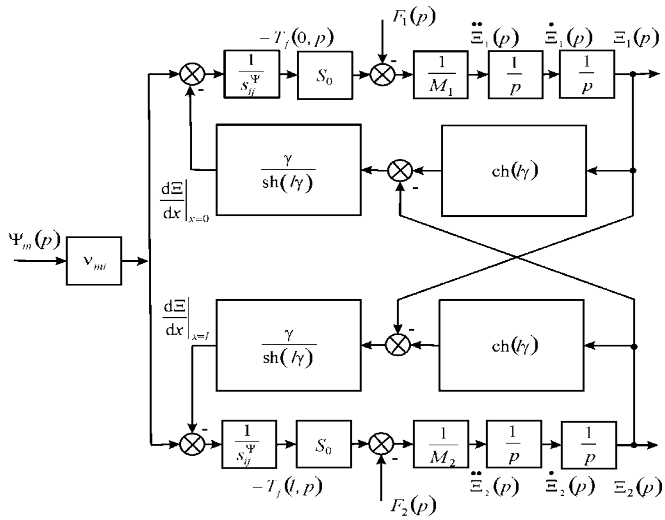

Figure 3: Generalized structural diagram of multilayer electro magneto elastic actuator

The Laplace transform of the caused force at the longitudinal piezo effect for the multilayer piezo actuator has the form

$$F(p) = d_{33} S_0 E_3(p) / s_{33}^E , \tag{11}$$

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

The structural-parametric model of the multilayer piezo actuator for the longitudinal piezo effect has the form

$$\Xi_1(p) = \left[\frac{1}{M_1 p^2}\right] \left\{ -F_1(p) + \left(\frac{1}{\chi_{33}^E}\right) \left[d_{33} E_3(p) - \left[\frac{\gamma}{\mathrm{sh}(l\gamma)}\right] \times \left[\mathrm{ch}(l\gamma)\Xi_1(p) - \Xi_2(p)\right]\right]\right\}$$

$$\Xi_2(p) = \left[\frac{1}{M_2 p^2}\right] \left\{ -F_2(p) + \left(\frac{1}{\chi_{33}^E}\right) \left[d_{33} E_3(p) - \left[\frac{\gamma}{\mathrm{sh}(l\gamma)}\right] \times \left[\mathrm{ch}(l\gamma)\Xi_2(p) - \Xi_1(p)\right]\right]\right\} \tag{12}$$

For the transverse piezo effect the Laplace transform of the caused force

$$F(p) = d_{31} S_0 E_3(p) / s_{11}^E \tag{13}$$

$$\chi_{11}^E = s_{11}^E / S_0$$

The structural-parametric model of the multilayer piezo actuator for the transverse piezo effect has the form

$$\Xi_1(p) = \left[\frac{1}{M_1 p^2}\right] \left\{ -F_1(p) + \left(\frac{1}{\chi_{11}^E}\right) \left[d_{31} E_3(p) - \left[\frac{\gamma}{\mathrm{sh}(l\gamma)}\right] \times \left[\mathrm{ch}(l\gamma)\Xi_1(p) - \Xi_2(p)\right]\right]\right\}$$

$$\Xi_2(p) = \left[\frac{1}{M_2 p^2}\right] \left\{ -F_2(p) + \left(\frac{1}{\chi_{11}^E}\right) \left[d_{31} E_3(p) - \left[\frac{\gamma}{\mathrm{sh}(l\gamma)}\right] \times \left[\mathrm{ch}(l\gamma)\Xi_2(p) - \Xi_1(p)\right]\right]\right\} \tag{14}$$

For the shift piezo effect the Laplace transform of the caused force

$$F(p) = d_{15} S_0 E_1(p) / s_{55}^E \tag{15}$$

$$\chi_{55}^E = s_{55}^E / S_0$$

The structural-parametric model of the multilayer piezo actuator for the shift piezo effect has the form

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

(16)

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

We drew the structural schematic diagram of the actuator from the generalized structural-parametric model of the multilayer electro magneto elastic actuator for the nanomechanics.

III. Matrix Transfer Function

From equation (10) we receive the matrix transfer function of the multilayer electro magneto elastic actuator with *n* the layers in the following form

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

Therefore, in general, we have the matrix transfer function of the multilayer electro magneto elastic actuator in the form

$$[\Xi(p)]=[W(p)][P(p)]$$

$$[\Xi(p)]=\begin{bmatrix}\Xi_1(p)\\ \Xi_2(p)\end{bmatrix}\ [W(p)]=\begin{bmatrix}W_{11}(p) & W_{12}(p) & W_{13}(p)\\ W_{21}(p) & W_{22}(p) & W_{23}(p)\end{bmatrix}\ [P(p)]=\begin{bmatrix}\Psi_m(p)\\ F_1(p)\\ F_2(p)\end{bmatrix} \quad (18)$$

where $[\Xi(p)]$, $[W(p)]$, $[P(p)]$ are the matrices of the displacements, the transfer functions and the control parameters

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

$$\chi_{ij}^{\Psi}=s_{ij}^{\Psi}/S_0$$

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

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

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

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

$$W_{13}(p)=\Xi_1(p)/F_2(p)=$$

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

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

We receive the generalized parametric structural schematic diagram and the generalized matrix transfer function from the generalized structural-parametric model of the multilayer electro magneto elastic actuator to calculate its static and dynamic characteristics for the nanomechanics. Let us consider, for example, the voltage-controlled multilayer piezo actuator for the longitudinal piezo effect with the inertial load $m << M_1$, $m << M_2$ and $F_1(t)=F_2(t)=0$ and the static displacements of its faces in the following form

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

thus

$$\xi_1(\infty)=d_{33}nU_m\,M_2/(M_1+M_2)$$

and

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

thus

$$\xi_2(\infty)=d_{33}nU_m\,M_1/(M_1+M_2)$$

where U_m is the amplitude of the voltage, m is the mass of the multilayer piezo actuator, M_1, M_2 are the load masses. For the voltage-controlled multilayer piezo actuator from the piezo ceramics PZT at d_{33} = 4·10^{-10} m/V, n = 8, U = 150 V, M_1 = 1.5 kg and M_2 = 6 kg we obtain the static displacements of the faces of the multilayer piezoactuator $\xi_1(\infty)$ = 384 nm, $\xi_2(\infty)$ = 96 nm, $\xi_1(\infty)+\xi_2(\infty)$ = 480 nm.

We derive the transfer function with concentrated parameters of the multilayer piezo actuator for the longitudinal piezo effect with the voltage control for the elastic-inertial load and one fixed face and its structural diagram in Figure 4.

$$W(p)=\frac{\Xi_2(p)}{U(p)}=\frac{d_{33}n}{\left(1+C_e/C_{33}^E\right)\left(T_t^2p^2+2T_t\xi_t p+1\right)} \qquad (19)$$

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

where $U(p)$ is the Laplace transform the voltage, T_t, ξ_t are the time constant and the damping coefficient, $C_{33}^E=S_0/\left(s_{33}^E l\right)$ is the rigidity.

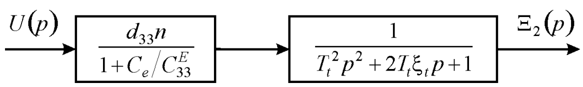

Figure 4: Structural diagram of voltage-controlled multilayer piezo actuator for longitudinal piezo effect and elastic-inertial load

Let us construct from (19) the transient response of the multilayer piezo actuator for the longitudinal piezo electric effect with the voltage control. This expression for the transient response of the voltage-controlled the multilayer piezo actuator for the longitudinal piezo effect and elastic-inertial load is determined in the form

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

$$\xi_m=\frac{d_{33}nU_m}{1+C_e/C_{33}^E},\quad \omega_t=\sqrt{1-\xi_t^2}\Big/T_t,\quad \varphi_t=\mathrm{arctg}\left(\sqrt{1-\xi_t^2}\Big/\xi_t\right)$$

where ξ_m is the steady-state value of displacement and U_m is the amplitude of the voltage. For the voltage-controlled multilayer piezo actuator with one fixed face from the piezo ceramics PZT with the longitudinal piezo effect and elastic-inertial load we obtain at $M_1\to\infty$, $m<<M_2$, U_m = 60 V, d_{33} = $4\cdot10^{-10}$ m/V, n = 10, M_2 = 4 kg, C_{33}^E = $6\cdot10^7$ N/m, C_e = $0.4\cdot10^7$ N/m the steady-state value of the displacement ξ_m = 225 nm and the time constant T_t = $0.25\cdot10^{-3}$ s. The discrepancy between the experimental data and calculation results is no more than 5%.

IV. Results and Discussions

We have the equations for the generalized structural-parametric model and the generalized structural diagram of the multilayer electro magneto elastic actuator. We receive the matrix transfer functions and the structural diagram of the multilayer electro magneto elastic actuator from the set of equations describing the structural parametric model of the multilayer actuator for the nanomechanics. The solution of the matrix equation for the equivalent quadripole of the multilayer electro magneto elastic actuator with the Laplace transform is used for the construction the structural diagram of the multilayer actuator.

As a result of the joint solution of the general equation of electro magneto elasticity, the matrix equation for the equivalent quadripole of the multilayer electro magneto elastic actuator, and its boundary conditions we receive the generalized structural-parametric model and the generalized structural diagram of the multilayer actuator.

V. Conclusion

We consider the generalized structural-parametric model, the structural diagram and the matrix transfer function of the multilayer electro magneto elastic actuator for the nanomechanics. We receive the structural diagram of the multilayer piezo actuator for the transverse, longitudinal, and shift piezo effects.

From the general equation of electro magneto elasticity, the force that causes the deformation, the system of the equations for the equivalent quadripole of the multilayer actuator, and the forces on its faces, we obtain generalized structural-parametric model and generalized structural diagram of the multilayer electro magneto elastic actuator for the nanomechanics.

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