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Structural Diagram of Actuator for Nanobiotechnology

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Abstract

The structural diagram of an electro magnetoelastic actuator for nanobiotechnology is obtained. The structural diagram of an electro magnetoelastic actuator has a difference in the visibility of energy conversion from the circuit of a piezo vibrator. The electro magnetoelasticity equation and the differential equation are solved to construct the structural diagram and model of the actuator. The structural diagram of the piezo actuator is obtained by using the reverse and direct piezoelectric effects. The structural model of the piezo actuator for control systems in nanobiotechnology is written. The transfer functions of the electro magnetoelastic actuator are obtained.

Keywords: Structural diagram and model; Actuator; Nanobiotechnology; Electro magnetoelastic actuator; Piezo actuator; Deformation; Transfer function

Introduction

Electro magnetoelastic actuators in the form of piezo actuators or magnetostriction actuators are used in nanomanipulators, laser systems, nano pumps, scanning and nanomanipulation in nanobiotechnology [1-6]. The piezo actuator is used for nano displacements in photolithography, in medical equipment for precise instrument delivery during microsurgical operations, in optical-mechanical devices, in adaptive optics systems, and in adaptive telescopes. It is also used in stabilization systems for optical-mechanical devices, systems for alignment and tuning of lasers, interferometers, adaptive optical systems and fiber-optic systems for transmitting and receiving information [4-12].

The electromagnetoelasticity equation and the differential equation are solved to obtain the structural model of the actuator. The structural diagram of the actuator has a difference in the visibility of energy conversion for from Cady and Mason electrical equivalent circuits of a piezo vibrator. The structural diagram of the actuator for nanobiotechnology is obtained by applying the theory of electro magnetoelasticity [4-8].

Structural Diagram

The structural diagram of an electro magnetoelastic actuator for nanobiotechnology is changed from Cady and Mason electrical equivalent circuits [4-8]. The equation of electro magnetoelasticity [2-14] has the form of the equation of the reverse effect for the actuator

$$S_i = d_{mi}\Psi_m + s_{ij}^{\Psi}T_j$$

where S_i, d_{mi}, Ψ_m, s_{ij}^{Ψ} and T_j are the relative deformation, the module, the control parameter or the intensity of field, the elastic compliance, and the mechanical intensity, respectively; $i = 1, 2, \dots, 6$; $m = 1, 2, 3$; and $j = 1, 2, \dots, 6$.

The equation of the force on the face of actuator has the form [10-15]

$$M\, d^2\xi(x,t)/dt^2 + F = S_0 T$$

where M, F, ξ, x, t, S_0 are the mass and the force of load, the displacement, the coordinate, the time, the area of actuator.

The differential equation of the actuator has the form [4-29]

$$d^2\Xi(x,p)/dx^2 - \gamma^2\Xi(x,p) = 0$$

$$\gamma = p/c^{\Psi} + \alpha$$

where $\Xi(x,p)$ is the transform of Laplace for displacement; p, γ, c^{Ψ}, α are the operator of transform, the coefficient of wave propagation, the speed of sound, the coefficient of attenuation.

The decision of the differential equation of the actuator has the form

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

where C, B are the coefficients

The coefficients C, B have the form

$$C = (\Xi_1 e^{l\gamma} - \Xi_2)/[2\mathrm{sh}(l\gamma)]$$

$$B = (\Xi_2 - \Xi_1 e^{-l\gamma})/[2\mathrm{sh}(l\gamma)]$$

where $\Xi_1(p)$, $\Xi_1(p)$ are transforms displacement of faces 1 and 2 for the actuator.

The system of the equations for the forces on its faces is found [10-38]

$$M_1 p^2 \Xi_1(p) + F_1(p) = S_0 T_j(0,p)$$

$$-M_2 p^2 \Xi_2(p) - F_2(p) = S_0 T_j(l,p)$$

The system of the equations stresses acting on its faces has the form

$$T_j(0,p) = \frac{1}{s_{ij}^{\Psi}} \frac{d\Xi(x,p)}{dx}\bigg|_{x=0} - \frac{d_{mi}}{s_{ij}^{\Psi}} \Psi_m(p)$$

$$T_j(0,p) = \frac{1}{s_{ij}^{\Psi}} \frac{d\Xi(x,p)}{dx}\bigg|_{x=0} - \frac{d_{mi}}{s_{ij}^{\Psi}} \Psi_m(p)$$

The system of equations for the structural diagram on (Figure 1) and model of an actuator for nanobiotechnology has the form

$$\Xi_1(p) = (M_1 p^2)^{-1} \times \begin{Bmatrix} -F_1(p) + (1/\chi_{ij}^{\Psi}) \\ \times \begin{bmatrix} d_{mi}\Psi_m(p) + [\gamma/\mathrm{sh}(l\gamma)] \\ \times [\Xi_2(p) - \mathrm{ch}(l\gamma)\Xi_1(p)] \end{bmatrix} \end{Bmatrix}$$

$$\Xi_2(p) = (M_2 p^2)^{-1} \times \begin{Bmatrix} -F_2(p) + (1/\chi_{ij}^{\Psi}) \times \\ \times \begin{bmatrix} d_{mi}\Psi_m(p) + [\gamma/\mathrm{sh}(l\gamma)] \\ \times [\Xi_1(p) - \mathrm{ch}(l\gamma)\Xi_2(p)] \end{bmatrix} \end{Bmatrix}$$

where

$$\chi_{ij}^{\Psi} = s_{ij}^{\Psi}/S_0,\ d_{mi} = \begin{cases} d_{33}, d_{31}, d_{15} \\ d_{33}, d_{31}, d_{15} \end{cases},\ \Psi_m = \begin{cases} E_3, E_1 \\ H_3, H_1 \end{cases},\ s_{ij}^{\Psi} = \begin{cases} s_{33}^{E}, s_{11}^{E}, s_{55}^{E} \\ s_{33}^{H}, s_{11}^{H}, s_{55}^{H} \end{cases},\ \gamma = \begin{cases} \gamma^{E} \\ \gamma^{H} \end{cases},$$

E is the intensity of electric field, H is the intensity of magnetic field.

After conversion the system of the equations for the

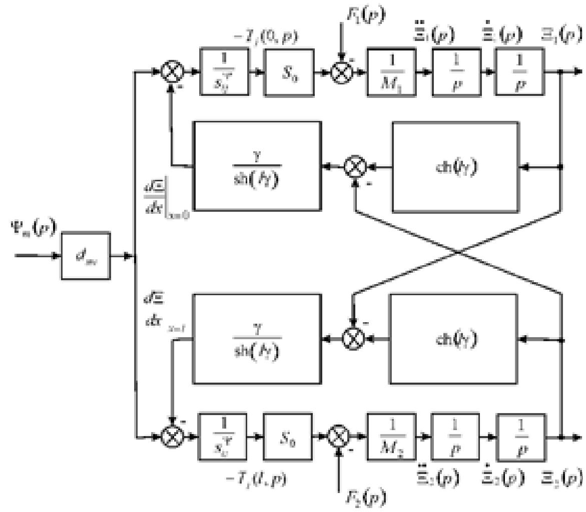

Figure 1: Structural diagram of actuator for nanobiotechnology.

structural model has form

$$\Xi_1(p) = (M_1 p^2)^{-1} \times \begin{Bmatrix} -F_1(p) + (1/\chi_{ij}^{\Psi}) \\ \times \begin{bmatrix} d_{mi}\Psi_m(p) - \gamma\mathrm{cth}(l\gamma)\Xi_1(p) \\ +(\gamma/\mathrm{sh}(l\gamma))\Xi_2(p) \end{bmatrix} \end{Bmatrix}$$

$$\Xi_2(p) = (M_2 p^2)^{-1} \times \begin{Bmatrix} -F_2(p) + (1/\chi_{ij}^{\Psi}) \\ \times \begin{bmatrix} d_{mi}\Psi_m(p) - \gamma\mathrm{cth}(l\gamma)\Xi_2(p) \\ +(\gamma/\mathrm{sh}(l\gamma))\Xi_1(p) \end{bmatrix} \end{Bmatrix}$$

Therefore, the system for the structural model is written as

$$\Xi_1(p) = (M_1 p^2)^{-1} \times \begin{Bmatrix} -F_1(p) + C_{ij}^{\Psi} l \\ \times \begin{bmatrix} d_{mi}\Psi_m(p) + [\gamma/\mathrm{sh}(l\gamma)] \\ \times [\Xi_2(p) - \mathrm{ch}(l\gamma)\Xi_1(p)] \end{bmatrix} \end{Bmatrix}$$

$$\Xi_2(p) = (M_2 p^2)^{-1} \times \begin{Bmatrix} -F_2(p) + C_{ij}^{\Psi} l \\ \times \begin{bmatrix} d_{mi}\Psi_m(p) + [\gamma/\mathrm{sh}(l\gamma)] \\ \times [\Xi_1(p) - \mathrm{ch}(l\gamma)\Xi_2(p)] \end{bmatrix} \end{Bmatrix}$$

where $C_{ij}^{\Psi} = S_0/(s_{ij}^{\Psi} l) = 1/(\chi_{ij}^{\Psi} l)$ is the stiffness of actuator at $\Psi = \mathrm{const}$.

After conversion the system of the equations has the form

$$\Xi_1(p) = W_{11}(p)\Psi_m(p) + W_{12}(p)F_1(p) + W_{13}(p)F_2(p)$$

$$\Xi_2(p) = W_{21}(p)\Psi_m(p) + W_{22}(p)F_1(p) + W_{23}(p)F_2(p)$$

or the matrix equation has the following form

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

The transfer functions have the form

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

$$W_{21}(p) = d_{mi}[M_1 \chi_{ij}^{\Psi} p^2 + \gamma \mathrm{th}(l\gamma/2)]/A_{ij}$$

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

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

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

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

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

Therefore, for the inertial load the steady-state displacements and of the actuator for nanobiotechnology have the form

$$\xi_1(t)|_{t \to \infty} = \xi_1(\infty) = d_{mi} \Psi_m l \, M_2 / (M_1 + M_2)$$

$$\xi_2(t)|_{t \to \infty} = \xi_2(\infty) = d_{mi} \Psi_m l \, M_1 / (M_1 + M_2)$$

The equation of the direct piezoelectric effect for the piezo actuator [10-14] has the form

$$D_m = d_{mi} T_i + \varepsilon_{mk}^{E} E_k$$

where D_m, ε_{mk}^{E} are the electric induction and the permittivity; $k = 1, 2, 3$.

For $E = \mathrm{const}$ the equation for the coefficient of the direct piezoelectric effect k_d for the piezo actuator has the form

$$k_d = \frac{I_{\dot{\Xi}_n}(p)}{\dot{\Xi}_n(p)} = \frac{d_{mi} S_0}{\delta s_{ij}^{E}}, n = 1, 2$$

where $I_{\dot{\Xi}_n}(p)$, $\dot{\Xi}_n(p)$ are transforms of current and velocity; is number of the face actuator.

The equation for negative feedback has the form ,

$$U_{\dot{\Xi}_n}(p) = \frac{d_{mi} S_0 R}{\delta s_{ij}^{E}} \dot{\Xi}_n(p) \, , n = 1, \; 2$$

After conversion (Figure 1) the structural diagram of the piezo actuator for nanobiotechnology has form (Figure 2)

The equation for the coefficient of the reverse piezoelectric effect is found in the form

$$k_r = k_d = \frac{d_{mi} S_0}{\delta s_{ij}^{E}}$$

The structural diagram of the piezo actuator for the lumped parameters is obtained on (Figure 3).

The transfer function of the piezo actuator for the lumped parameters on (Figure 3) at $R = 0$ has the form

$$W(p) = \frac{\Xi_2(p)}{U(p)} = \frac{k_r}{M_2 p^2 + k_v p + C_{ij}^{E} + C_e}$$

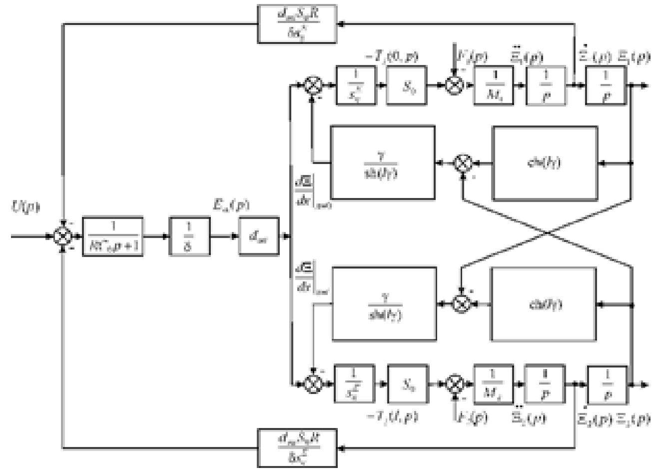

Figure 2: Structural diagram of piezo actuator for nanobiotechnology.

where $U(p)$ is transformations of the voltage for the piezo actuator.

After conversion the transfer function of the piezo actuator has the form

$$W(p) = \frac{\Xi_2(p)}{U(p)} = \frac{d_{mi}(l/\delta)}{\left(1 + C_e / C_{ij}^{E}\right)\left(T_t^2 p^2 + 2T_t \xi_t p + 1\right)}$$

$$T_t = \sqrt{M_2 / \left(C_{ij}^{E} + C_e\right)}, \quad \xi_t = k_v \Big/ \left(2\left(C_{ij}^{E} + C_e\right)\sqrt{M_2\left(C_{ij}^{E} + C_e\right)}\right)$$

$$C_{ij}^{E} = S_0 / \left(s_{ij}^{E} l\right) = 1 / \left(\chi_{ij}^{E} l\right)$$

where T_t is the time constant, ξ_t is the coefficient of attenuation, C_{ij}^{E} is the stiffness of the piezo actuator at $E = \mathrm{const}$.

For the transverse piezoelectric effect the transfer function of the piezo actuator has the form m

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

$$T_t = \sqrt{M_2 / (C_e + C_{11}^{E})}, \xi_t = \alpha h^2 C_{11}^{E} / \left(3c^{E}\sqrt{M(C_e + C_{11}^{E})}\right), C_{11}^{E} = S_0 / \left(s_{11}^{E} h\right) = 1 / \left(\chi_{11}^{E} h\right)$$

where h, δ are the height and the thickness.

For the step input voltage the transient process of the piezo actuator at the transverse piezoelectric effect has form

$$\xi_2(t) = \frac{d_{31}(h/\delta)U}{\left(1 + C_e / C_{11}^{E}\right)}\left(1 - \frac{e^{-\frac{\xi_t t}{T_t}}}{\sqrt{1 - \xi_t^2}} \sin(\omega_t t + \phi_t)\right)$$

$$\omega_t = \frac{\sqrt{1 - \xi_t^2}}{T_t}, \phi_t = \mathrm{arctg}\left(\frac{\sqrt{1 - \xi_t^2}}{\xi_t}\right)$$

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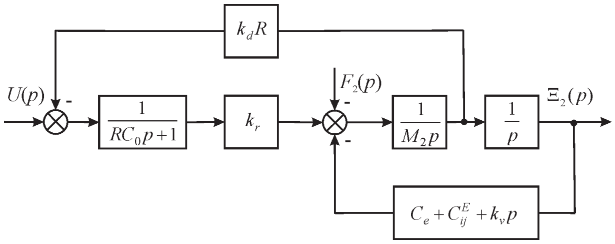

Figure 3: Structural diagram of piezo actuator at elastic-inertial load.

For the piezo actuator with the transverse piezoelectric effect made from ceramic PZT at d_{31}= $2\cdot10^{-10}$ m/V, h/δ =16, M_2 = 2 kg, C_{11}^E= $2.8\cdot10^7$ N/m, C_e = $0.4\cdot10^7$ N/m, U = 50 V, its parameters are obtained T_t = $0.25\cdot10^{-3}$ s and steady-state displacement $\xi_2(t)|_{t\to\infty} = \xi_2(\infty) = \Delta h = 140$ nm.

Characteristics

The characteristics of an electro magnetoelastic actuator for nanobiotechnology are obtained. The mechanical characteristic [10-38] of the actuator for nanobiotechnology is obtained as $S_i(T_j)$ or $\Delta l(F)$, for example,

$$S_i|_{\Psi=\text{const}} = d_{mi}\Psi_m|_{\Psi=\text{const}} + s_{ij}^{\Psi}T_j$$

The regulation line [12-26] of an electro magnetoelastic actuator is written as $S_i(\Psi_m)$ or $\Delta l(U)$, for example,

$$S_i|_{T=\text{const}} = d_{mi}\Psi_m + s_{ij}^{\Psi}T_j|_{T=\text{const}}$$

The mechanical characteristic of an electro magnetoelastic actuator for nanobiotechnology has the following form

$$\Delta l = \Delta l_{\max}\left(1 - F/F_{\max}\right)$$

Therefore, the maximum of the parameters $\Delta l_{\max}$ and $F_{\max}$ of the mechanical characteristic have the form

$$\Delta l_{\max} = d_{mi}\Psi_m l$$

$$F_{\max} = T_{j\max}S_0 = d_{mi}\Psi_m S_0/s_{ij}^{\Psi}$$

where index max is used for the maximum value of parameter.

For the transverse piezoelectric effect the maximum values of parameters of the piezo actuator for nanobiotechnology have the form

$$\Delta h_{\max} = d_{31}E_3h$$

$$F_{\max} = d_{31}E_3S_0/s_{11}^E$$

For the transverse piezo actuator for nanobiotechnology at d_{31} = $2\cdot10^{-10}$ m/V, E_3 = $1\cdot10^5$ V/m, h = $2.5\cdot10^{-2}$ m, S_0 = $1.5\cdot10^{-5}$ m^2, s_{11}^E= $15\cdot10^{-12}$ m^2/N its parameters on (Figure 4) are found $\Delta h_{\max}$ = 500 nm and $F_{\max}$ = 20 N.

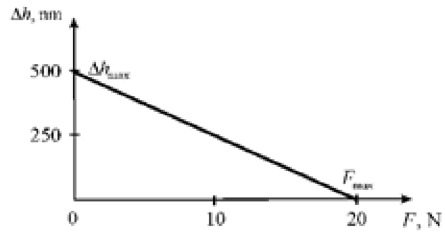

Figure 4: Mechanical characteristic of transverse piezo actuator.

At elastic load the regulation line of an electro magnetoelastic actuator for nanobiotechnology is obtained in the form

$$\frac{\Delta l}{l} = d_{mi}\Psi_m - \frac{s_{ij}^{\Psi}C_e}{S_0}\Delta l$$

$$F = C_e\Delta l$$

Therefore, the equation of the displacement at elastic load has the form

$$\Delta l = \frac{d_{mi}l\Psi_m}{1 + C_e/C_{ij}^{\Psi}}$$

For the transverse piezoelectric effect of the piezo actuator for nanobiotechnology the equation of the displacement at elastic load has the form

$$\Delta h = \frac{(d_{31}h/\delta)U}{1 + C_e/C_{11}^E} = k_{31}^U U$$

$$k_{31}^U = (d_{31}h/\delta)/(1 + C_e/C_{11}^E)$$

where k_{31}^U is the transfer coefficient.

For the transverse piezo actuator at d_{31} = $2\cdot10^{-10}$ m/V, h/δ = 16, C_{11}^E= $2.8\cdot10^7$ N/m, C_e = $0.4\cdot10^7$ N/m, U = 100 V, its parameters are found k_{31}^U= 2.8 nm/V and steady-state displacement $\xi_2(t)\big|_{t\to\infty} = \xi_2(\infty) = \Delta h =$ 280 nm. Theoretical and practical parameters are coincidences with an error of 10%.

For calculations the mechatronics control systems in nanobiotechnology with an electro magnetoelastic actuator its characteristics are found.

Conclusion

The structural diagram of an electro magnetoelastic actuator for nanobiotechnology is obtained. The structural diagram of an electro magnetoelastic actuator has a difference in the visibility of energy conversion from the circuit of a piezo vibrator. The structural diagram of an electro magnetoelastic actuator for nanotechnology is changed from Cady and Mason electrical equivalent circuits of a piezo vibrator.

The structural diagram of an electro magnetoelastic actuator is found from its electro magnetoelasticity and differential equations. The structural diagram of the piezo actuator is obtained using the reverse and direct piezoelectric effects. The back electromotive force for the piezo actuator is written from the direct piezoelectric effect. The characteristics of an electro magnetoelastic actuator for nanobiotechnology are obtained. The regulation line of the piezo actuator is found.

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