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Structural scheme of an electro elastic actuator for nano displacement

Sergey M. Afonin
National Research University of Electronic Technology, MIET, Moscow, Russia
Email: *eduems@mail.ru*

Abstract. The structural model of an electro elastic actuator is determined for nano displacement. The structural scheme of an electro elastic actuator is obtained for nanotechnology. The matrix equation of an electro elastic actuator is constructed. The characteristics of a nano piezo actuator are evaluated. The transfer function of a nano piezo actuator is calculated. The mechanical characteristic of the nano transverse piezo actuator is obtained. The transfer function and coefficient of the nano transverse piezo actuator are calculated.

Keywords. Electro elastic actuator, nano piezo actuator, structural scheme, deformation matrix, nano displacement.

1. Introduction

An electro elastic actuator with the piezoelectric or electrostriction effects is used for nano displacement in nanotechnology, nanomedicine, nanobiology [1-8]. The piezoelectric materials are applied for an actuator and a resonator in science recearch [6-12]. The nano piezo actuator is promised in microsurgery, clinical medical and genetic research, scanning microscopy, adaptive optics, communications systems, big compound telescopes, satellite antennas [12-20].

2. Structural Scheme

Let us consider calculation the structural model of a nano piezo actuator. The expression of the reverse piezo effect [1-29]

$$S_i = d_{mi} E_m + s_{ij}^E T_j$$

here T_j - the mechanical stress, s_{ij}^E - the elastic compliance for $E = \text{const}$, E_m - the electric field strength, d_{mi} - the piezo module, S_i - the relative deformation, *i*, *j*, *m* - the indexes

The expression of the inverse piezo effect for the nano shif piezo actuator [1-29] is written

$$S_5 = d_{15} E_1 + s_{55}^E T_5$$

The differential equation of a nano piezo actuator is calculated [4-62]

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

here $\Xi(x,s)$, x , s, γ are the transform for the deformation, the coordinate, the parameter, the coefficient of the propagation.

For the nano shif piezo actuator at $x = 0$ $\Xi(0,s) = \Xi_1(s)$ and $x = b$ $\Xi(b,s) = \Xi_2(s)$ its solution is determined

$$\Xi(x,s) = \{\Xi_1(s)\text{sh}[(b-x)\gamma] + \Xi_2(s)\text{sh}(x\gamma)\}/\text{sh}(b\gamma)$$

At $x = 0$ and $x = b$ the expressions [12-40] are written

$$T_5(0,s) = \frac{1}{s_{55}^E} \left.\frac{d\Xi(x,s)}{dx}\right|_{x=0} - \frac{d_{15}}{s_{55}^E} E_1(s)$$

$$T_5(b,s) = \frac{1}{s_{55}^E} \left.\frac{d\Xi(x,s)}{dx}\right|_{x=b} - \frac{d_{15}}{s_{55}^E} E_1(s)$$

The structural model of the nano shif piezo actuator is calculated

$$\Xi_1(s) = \left(M_1 s^2\right)^{-1} \left\{ \begin{array}{l} -F_1(s) + \left(\chi_{55}^E\right)^{-1} \\ \times \left[\begin{array}{l} d_{15} E_1(s) - [\gamma / \mathrm{sh}(b\gamma)] \\ \times [\mathrm{ch}(b\gamma) \Xi_1(s) - \Xi_2(s)] \end{array} \right] \end{array} \right\}$$

$$\Xi_2(s) = \left(M_2 s^2\right)^{-1} \left\{ \begin{array}{l} -F_2(s) + \left(\chi_{55}^E\right)^{-1} \\ \times \left[\begin{array}{l} d_{15} E_1(s) - [\gamma / \mathrm{sh}(b\gamma)] \\ \times [\mathrm{ch}(b\gamma) \Xi_2(s) - \Xi_1(s)] \end{array} \right] \end{array} \right\}$$

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

The expression of the transverse inverse piezo effect [1-29]

$$S_1 = d_{31} E_3 + s_{11}^E T_1$$

The solution of the differential equation is calculated

$$\Xi(x,s) = \{\Xi_1(s) \mathrm{sh}[(h-x)\gamma] + \Xi_2(s) \mathrm{sh}(x\gamma)\} / \mathrm{sh}(h\gamma)$$

The system at $x = 0$ and $x = h$ is calculated

$$T_1(0,s) = \frac{1}{s_{11}^E} \left. \frac{d\Xi(x,s)}{dx} \right|_{x=0} - \frac{d_{31}}{s_{11}^E} E_3(s)$$

$$T_1(h,s) = \frac{1}{s_{11}^E} \left. \frac{d\Xi(x,s)}{dx} \right|_{x=h} - \frac{d_{31}}{s_{11}^E} E_3(s)$$

The structural model of the nano transverse piezo actuator is determined

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

$$\Xi_2(s) = \left(M_2 s^2\right)^{-1} \left\{ \begin{array}{l} -F_2(s) + \left(\chi_{11}^E\right)^{-1} \\ \times \left[\begin{array}{l} d_{31} E_3(s) - [\gamma / \mathrm{sh}(h\gamma)] \\ \times [\mathrm{ch}(h\gamma) \Xi_2(s) - \Xi_1(s)] \end{array} \right] \end{array} \right\}$$

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

The expression of the longitudinal inverse piezo effect [1-29]

$$S_3 = d_{33} E_3 + s_{33}^E T_3$$

The solution is calculated

$$\Xi(x,s) = \{\Xi_1(s) \mathrm{sh}[(\delta-x)\gamma] + \Xi_2(s) \mathrm{sh}(x\gamma)\} / \mathrm{sh}(\delta\gamma)$$

The system at $x = 0$ and $x = \delta$ is calculated

$$T_3(0,s) = \frac{1}{s_{33}^E} \left. \frac{d\Xi(x,s)}{dx} \right|_{x=0} - \frac{d_{33}}{s_{33}^E} E_3(s)$$

$$T_3(\delta,s) = \frac{1}{s_{33}^E} \left. \frac{d\Xi(x,s)}{dx} \right|_{x=\delta} - \frac{d_{33}}{s_{33}^E} E_3(s)$$

The structural model of the nano longitudinal piezo actuator is determined

$$\Xi_1(s) = \left(M_1 s^2\right)^{-1} \left\{ \begin{array}{l} -F_1(s) + \left(\chi_{33}^E\right)^{-1} \\ \times \left[\begin{array}{l} d_{33} E_3(s) - [\gamma/\mathrm{sh}(\delta\gamma)] \\ \times [\mathrm{ch}(\delta\gamma)\Xi_1(s) - \Xi_2(s)] \end{array} \right] \end{array} \right\}$$

$$\Xi_2(s) = \left(M_2 s^2\right)^{-1} \left\{ \begin{array}{l} -F_2(s) + \left(\chi_{33}^E\right)^{-1} \\ \times \left[\begin{array}{l} d_{33} E_3(s) - [\gamma/\mathrm{sh}(\delta\gamma)] \\ \times [\mathrm{ch}(\delta\gamma)\Xi_2(s) - \Xi_1(s)] \end{array} \right] \end{array} \right\}$$

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

In general at $l = \{ \delta, h, b$ the solution is calculated

$$\Xi(x,s) = \{\Xi_1(s)\mathrm{sh}[(l-x)\gamma] + \Xi_2(s)\mathrm{sh}(x\gamma)\}/\mathrm{sh}(l\gamma)$$

The system is transformed

$$T_j(0,s) = \frac{1}{s_{ij}^\Psi} \left.\frac{d\Xi(x,s)}{dx}\right|_{x=0} - \frac{\nu_{mi}}{s_{ij}^\Psi}\Psi_m(s)$$

$$T_j(l,s) = \frac{1}{s_{ij}^\Psi} \left.\frac{d\Xi(x,s)}{dx}\right|_{x=l} - \frac{\nu_{mi}}{s_{ij}^\Psi}\Psi_m(s)$$

The structural model an electro elastic actuator is calculated for nano displacement on Figure 1

$$\Xi_1(s) = \left(M_1 s^2\right)^{-1} \left\{ \begin{array}{l} -F_1(s) + \left(\chi_{ij}^\Psi\right)^{-1} \\ \times \left[\begin{array}{l} \nu_{mi} \Psi_m(s) - [\gamma/\mathrm{sh}(l\gamma)] \\ \times [\mathrm{ch}(l\gamma)\Xi_1(s) - \Xi_2(s)] \end{array} \right] \end{array} \right\}$$

$$\Xi_2(s) = \left(M_2 s^2\right)^{-1} \left\{ \begin{array}{l} -F_2(s) + \left(\chi_{ij}^\Psi\right)^{-1} \\ \times \left[\begin{array}{l} \nu_{mi} \Psi_m(s) - [\gamma/\mathrm{sh}(l\gamma)] \\ \times [\mathrm{ch}(l\gamma)\Xi_2(s) - \Xi_1(s)] \end{array} \right] \end{array} \right\}$$

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

$$v_{mi} = \begin{cases} d_{33}, d_{31}, d_{15} \\ g_{33}, g_{31}, g_{15} \end{cases}$$

$$\Psi_m = \begin{cases} E_3, E_1 \\ D_3, D \end{cases}$$

$$s_{ij}^\Psi = \begin{cases} s_{33}^E, s_{11}^E, s_{55}^E \\ s_{33}^D, s_{11}^D, s_{55}^D \end{cases}$$

$$\gamma = \{\gamma^E, \gamma^D,$$

$$c^\Psi = \{ c^E, c^D$$

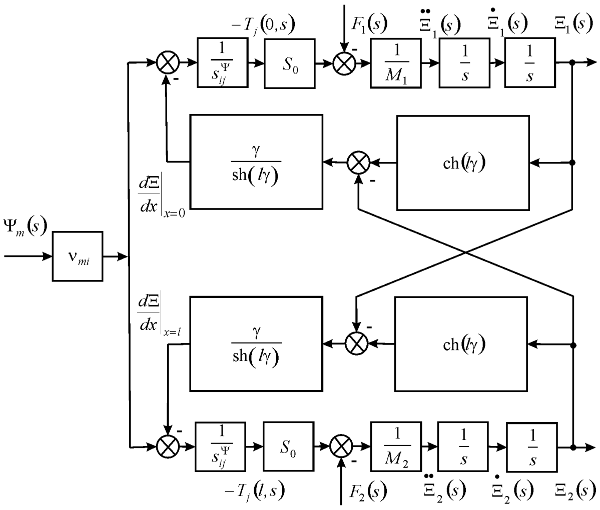

Figure 1. Scheme of actuator

The deformation matrix is calculated

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

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

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

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

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

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

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

In static the longitudinal deformations

$$\xi_1 = d_{33}UM_2/(M_1+M_2)$$

$$\xi_2 = d_{33}UM_1/(M_1+M_2)$$

For d_{33} = 4·10^{-10} m/V, U = 125 V, M_1 = 1 kg, M_2 = 4 kg the static deformations ξ_1 = 40 nm, ξ_2 = 10 nm and $\xi_1 + \xi_2$ = 50 nm are determined at error 10%.

The expression of the direct piezo effect has form [1-21]

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

here ε_{mk}^{E} - the permittivity and D_m - the electric induction.

The back electromotive force on Figure 2 is evaluated

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

For a nano piezo actuator its direct and reverse coefficients are calculated

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

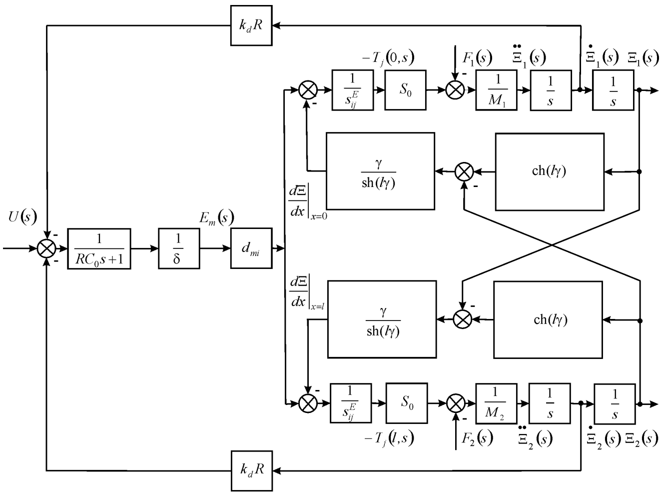

Figure 2. Scheme of nano piezo actuator

For the nano transverse piezo actuator the mechanical characteristic is evaluated

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

$$\Delta h_{\max} = d_{31} E_3 h$$

$$F_{\max} = d_{31} E_3 S_0 / s_{11}^E$$

At d_{31} = 2·10^{-10} m/V, E_3 = 0.6·10^5 V/m, h = 2.5·10^{-2} m, S_0 = 1.5·10^{-5} m^2, s_{11}^E = 15·10^{-12} m^2/N the values $\Delta h_{\max}$ = 300 nm and $F_{\max}$ = 12 N are found at error 10%.

In static the deformation of a nano piezo actuator

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

$$F = C_e \Delta l$$

The adjustment characteristic of a nano piezo actuator is determined

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

The transfer function for Figure 3 is evaluated

$$W(s) = \Xi_2(s)/U(s) = k_r / N(s)$$

$$N(s) = a_0 s^3 + a_1 s^2 + a_2 s + a_3$$

$$a_0 = RC_0 M_2, \; a_1 = M_2 + RC_0 k_v$$

$$a_2 = k_v + RC_0 C_{ij} + RC_0 C_e + Rk_r k_d, \; a_3 = C_e + C_{ij}$$

here k_v is the speed damping coefficient.

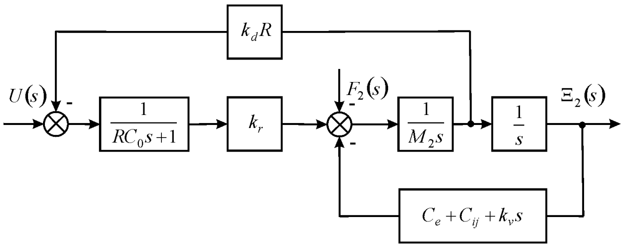

Figure 3. Scheme of nano piezo actuator at one fixed face

At $R = 0$ the expression for the nano transverse piezo actuator is evaluated

$$W(s) = \frac{\Xi(s)}{U(s)} = \frac{k_{31}^U}{T_t^2 s^2 + 2T_t \xi_t s + 1}$$

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

$$T_t = \sqrt{M/\left(C_l + C_{11}^E\right)}, \quad \omega_t = 1/T_t$$

For M = 4 kg, C_l = 0.2·10^7 N/m, C_{11}^E = 2·10^7 N/m the values T_t = 0.43·10^{-3} s, ω_t = 2.3·10^3 s^{-1} are calculated at error 10%.

The static deformation of nano transverse piezo actuator

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

At d_{31} = 2·10^{-10} m/V, C_l / C_{11}^E = 0.1, h/δ = 24 its transfer coefficient k_{31}^U =4.4 nm/V is determined at error 10%.

3. Conclusions

The structural model of an electro elastic actuator is constructed. The deformation matrix is determined. The scheme and characteristics of a nano piezo actuator are obtained. The mechanical characteristic of the nano transverse piezo actuator is evaluated. The transfer function of the nano transverse piezo actuator is calculated.

Conflicts of Interest

The authors declare no conflict of interest.

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