ISSN: 2149-2018

Applied Medical Research, 2023
VOL 10, NO. 2, PAGE 1 – 6
DOI: doi.org/10.47363/AMR/2023(10)229

RESEARCH ARTICLE

Open Access

Structural Model of a Nano Drive for Biomedical Research

Afonin SM

National Research University of Electronic Technology, MIET, Moscow, Russia

ABSTRACT

The structural model of a nano drive is determined for biomedical research. The structural scheme of the piezo drive is obtained. The matrix equation is constructed for a nano drive.

ARTICLE HISTORY

Received September 17, 2023
Accepted September 26, 2023
Published September 30, 2023

Keywords: Nano Drive, Piezo Drive, Structural Model and Scheme, Matrix Equation, Biomedical Research

Introduction

A nano drive based on the piezomagnetic, magnetostriction, piezoelectric, electrostriction effects is used for biomedical research, nanomedicine, nanotechnology, nanobiology, microsurgery. The piezo drive is used in scanning microscopy, astronomy for alignment and focusing, image stabilization, in adaptive optics and work with the genes [1-9].

Structural Model

The expression of electromagnetoelasticity [1-15] has the forn

$$S_i = s_{ij}^{E,H} T_j + d_{mi}^{H} E_m + d_{mi}^{E,} H_m$$ - the piezo module,

here T_j- the mechanical stress, E_m - the electric field strength, H_m- the magnetic field strength, $s_{ij}^{E,H}$ - the elastic compliance for E= const, H = const, d_{mi}^{H} - the piezo module, d_{mi}^{E} - the magnetostriction coefficient, S_i - the relative deformation, the axis i, j, m.

Therefore, the expression of the reverse piezo effect [1-15]

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

and the expression of the magnetostrictive effect [1-15]

$$S_i = d_{mi} H_m + s_{ij}^{H} T_j$$

The expression of the shift inverse piezo effect [1-15]

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

The differential equation of a nano drive is calculated [4-58]

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

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

For the shif piezo drive at $x = 0$ $\Xi(0,s) = \Xi_1(s)$ and at and $x = b$ $\Xi(b,s) = \Xi_2(s)$ the solution of this differential equation is calculated

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

At x=0 and x=b the expressions [11-39] 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

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

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

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

The expression of the shift magnetostrictive effect [1-15]

$$S_5 = d_{15} H_1 + s_{55}^{H} T_5$$

Contact Afonin SM National Research University of Electronic Technology, MIET, 124498, Moscow, Russia.

The structural model is transformed

$$\Xi_1(s) = \left(M_1 s^2\right)^{-1} \left\{ \begin{array}{l} -F_1(s) + \left(\chi_{55}^H\right)^{-1} \\ \times \left[\begin{array}{l} d_{15} H_1(s) - [\gamma/\mathrm{sh}(b\gamma)] \\ \times [\mathrm{ch}(b\gamma)\Xi_1(s) - \Xi_2(s)] \end{array} \right] \end{array} \right\}$$

$$\Xi_2(s) = \left(M_2 s^2\right)^{-1} \left\{ \begin{array}{l} -F_2(s) + \left(\chi_{55}^H\right)^{-1} \\ \times \left[\begin{array}{l} d_{15} H_1(s) - [\gamma/\mathrm{sh}(b\gamma)] \\ \times [\mathrm{ch}(b\gamma)\Xi_2(s) - \Xi_1(s)] \end{array} \right] \end{array} \right\}$$

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

The expression of the transverse inverse piezo effect [1-15]

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

The solution 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

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

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

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

The expression of the transverse magnetostrictive effect [1-15]

$$S_1 = d_{31} H_3 + s_{11}^H T_1$$

The structural model is transformed

$$\Xi_1(s) = \left(M_1 s^2\right)^{-1} \left\{ \begin{array}{l} -F_1(s) + \left(\chi_{11}^H\right)^{-1} \\ \times \left[\begin{array}{l} d_{31} H_3(s) - [\gamma/\mathrm{sh}(h\gamma)] \\ \times [\mathrm{ch}(h\gamma)\Xi_1(s) - \Xi_2(s)] \end{array} \right] \end{array} \right\}$$

$$\Xi_2(s) = \left(M_2 s^2\right)^{-1} \left\{ \begin{array}{l} -F_2(s) + \left(\chi_{11}^H\right)^{-1} \\ \times \left[\begin{array}{l} d_{31} H_3(s) - [\gamma/\mathrm{sh}(h\gamma)] \\ \times [\mathrm{ch}(h\gamma)\Xi_2(s) - \Xi_1(s)] \end{array} \right] \end{array} \right\}$$

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

In general at l = { δ, 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 on Figure 1 is calculated

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

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

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

$$\nu_{mi} = \left\{ \begin{array}{l} d_{33}, d_{31}, d_{15} \\ g_{33}, g_{31}, g_{15} \\ d_{33}, d_{31}, d_{15} \end{array} \right.$$

$$\Psi_m = \left\{ \begin{array}{l} E_3, E_1 \\ D_3, D_1 \\ H_3, H_1 \end{array} \right.$$

$$s_{ij}^\Psi = \left\{ \begin{array}{l} s_{33}^E, s_{11}^E, s_{55}^E \\ s_{33}^D, s_{11}^D, s_{55}^D \\ s_{33}^H, s_{11}^H, s_{55}^H \end{array} \right.$$

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

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

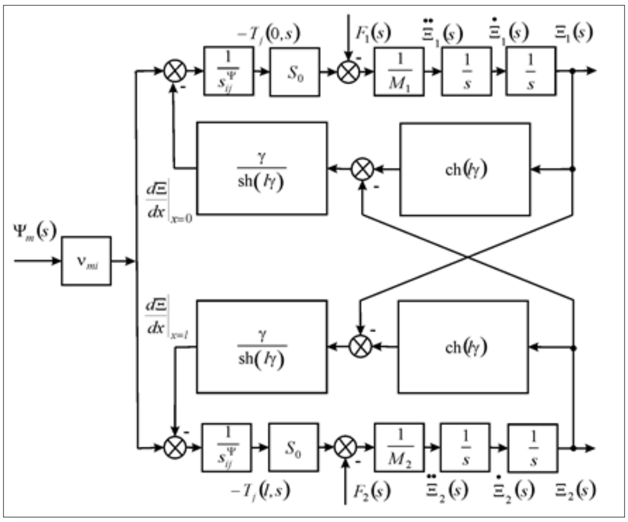

Figure 1: Scheme of Nano Drive

The matrix of deformations is calculated

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

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

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

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

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

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

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

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 $d_{33}=4\cdot10^{-10}$ m/V, $U=75$ V, $M_1=1$ kg, $M_2=4$ kg the static deformations $\xi_1=24$ nm, $\xi_2=6$ nm and $\xi_1+\xi_2=30$ nm are calculated at error 10%.

The expression of the direct piezo effect has form [1-15]

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

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

The transform for the back electromotive force on Figure 2 is evaluated

$$U_d(s)=\frac{d_{mi}S_0R}{\delta s_{ij}^{E}}\dot{\Xi}_n(s)=k_dR\dot{\Xi}_n(s),\ n=1,2$$

The reverse and direct coefficients are calculated

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

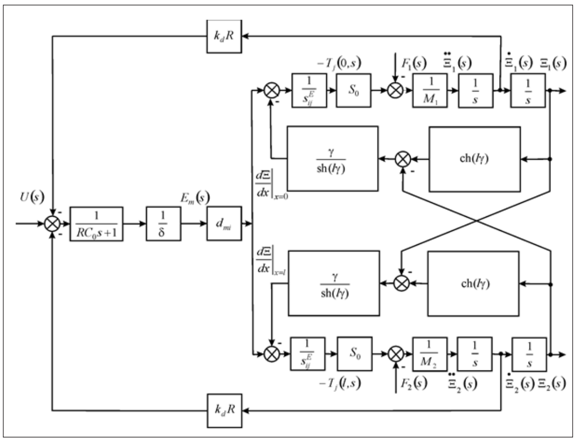

Figure 2: Scheme of Piezo Drive

At voltage control of the piezo drive its characteristis are evaluated

$$T_{j\max}=E_md_{mi}/s_{ij}^{E}$$

$$F_{\max}=E_md_{mi}S_0/s_{ij}^{E}$$

At current control of the piezo drive

$$F_{\max}=\frac{U}{\delta}d_{mi}\frac{S_0}{s_{ij}^{E}}+\frac{F_{\max}}{S_0}d_{mi}S_c\frac{1}{\varepsilon_{mk}^{T}S_c/\delta}\frac{1}{\delta}d_{mi}\frac{S_0}{s_{ij}^{E}}$$

$$\frac{F_{\max}}{S_0}\left(1-\frac{d_{mi}^2}{\varepsilon_{mk}^{T}s_{ij}^{E}}\right)s_{ij}^{E}=E_md_{mi}$$

$$T_{j\max}\left(1-k_{mi}^2\right)s_{ij}^{E}=E_md_{mi}$$

$$k_{mi}=d_{mi}\Big/\sqrt{s_{ij}^{E}\varepsilon_{mk}^{T}}$$

$$T_{j\max}=E_md_{mi}/s_{ij}^{D}$$

$$F_{\max}=E_md_{mi}S_0/s_{ij}^{D}$$

$$s_{ij}^{D}=\left(1-k_{mi}^2\right)s_{ij}^{E}$$

here S_c - the sectional area of the capacitor, C_0 - the capacitance, k_{mi} - the electromechanical coupling coefficient.

For a nano drive the mechanical and adjustment characteristics [11-26] are evaluated

$$S_i(T_j)\big|_{\Psi=\text{const}} = \nu_{mi}\Psi_m\big|_{\Psi=\text{const}} + s_{ij}^{\Psi}T_j$$

$$S_i(\Psi_m)\big|_{T=\text{const}} = \nu_{mi}\Psi_m + s_{ij}^{\Psi}T_j\big|_{T=\text{const}}$$

The mechanical characteristic is written

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

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

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

Therefore, for the transverse piezo drive this 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 $d_{31} = 2\cdot10^{-10}$ m/V, $E_3 = 0.75\cdot10^5$ 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 the values $\Delta h_{\max}$ = 375 nm and $F_{\max}$ = 15 N are found at error 10%

In static the deformation of a nano drive

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

$$F = C_e\Delta l$$

The adjustment characteristic of a nano drive is evaluated

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

here $s_{ij} = k_s s_{ij}^{E}$ the elastic compliance, k_s - the coefficient of the change of elastic compliance

$$\left(1 - k_{mi}^2\right) \le k_s \le 1$$

The expression for Figure 3 is evaluated

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

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

$$a_0 = RC_0M_2,\ a_1 = M_2 + RC_0k_v$$

$$a_2 = k_v + RC_0C_{ij} + RC_0C_e + Rk_rk_d,\ a_3 = C_e + C_{ij}$$

here k_v is the speed damping coefficient.

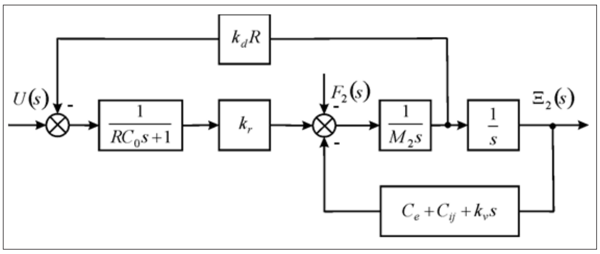

Figure 3: Scheme of Piezo Drive at One Fixed Face

At $R = 0$ the expression is evaluated

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

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

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

For M = 3 kg, $C_l = 0.1\cdot10^7$ N/m, $C_{11}^{E} = 1.8\cdot10^7$ N/m the values

$T_t = 0.4\cdot10^{-3}$ s, $\omega_t = 2.5\cdot10^3$ s^{-1} are calculated at error 10%.

The static deformation

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

For $d_{31} = 2\cdot10^{-10}$ m/V, h/δ = 30, C_l/C_{11}^{E} = 0.2

the coefficient k_{31}^{U} = 5 nm/V is determined at error 10%.

Conclusion

For a nano drive the structural model is evaluated. The matrix of the deformations is constructed. The characteristics of the piezo drive are determined for biomedical research.

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