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# A multi-layer electro elastic drive for micro and nano robotics


## Abstract

A multi-layer electro elastic drive of robotics is used in adaptive optics of compound telescope, scanning microscopy, interferometry and nanotechnology. For micro and nano robotics a multi-layer electro elastic drive is applied. The parametric model of a multi-layer electro elastic drive is determined. Its functions and matrix deformations are founded. The parameters of the multi-layer longitudinal PZT drive are determined.


**Keywords:** multi-layer electro elastic drive, multi-layer piezo drive, parametric model, micro and nano robotics.

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## Introduction

A multi-layer electro elastic drive is used promising for micro and nano robotics in the micro and nano displacement.[1–8] This drive based on the piezoelectric or electrostriction effects.[9–19] A multi-layer electro elastic drive of robotics is applied in adaptive optics of compound telescope, scanning microscopy, micro surgery, interferometry, nano pump, nano stabilization and nanotechnology.[20–53] The deformations of a multi-layer drive are described with the matrix equation. Its parametric model, scheme and functions are obtained by using of mathematical physics method. Parametric model

### Parametric model

The parametric model[6–53] of multi-layer piezo actuator with the voltage or current controlled are determined using the equation of inverse piezo effect in the form at the control of voltage

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

at the control of current

$$S_i = g_{mi} D_m + s_{ij}^D T_j$$

here $S_i$, $E_m$, $D_m$, $T_j$, $d_{mi}$, $g_{mi}$, $s_{ij}^E$, $s_{ij}^D$ are the relative deformation, the strength of electric field, the electric induction, the strength of mechanic field, the piezo module, the piezo constant, the elastic compliances at $E = \text{const}$ and at $D = \text{const}$, and $i, j, m$ are the indexes.

The equation of the direct piezo effect has the form[6–53]

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

here $\varepsilon_{mk}^T$ is the dielectric constants at $T = \text{const}$, $k$ is the index

Then the electroelasticity equation of a multi-layer drive[6–53] has the form

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

here $\Psi = E, D$ is control parameter at the control of voltage and the control of current.

A multi-layer drive consist from the piezo layers connected the series mechanically and the parallel electrically [6 – 44]. We have the system of equations for $T$-form quadripole of $k$ piezo layer

$$F_{k\text{ inp}}(s) = -(Z_1 + Z_2)\Xi_k(s) + Z_2 \Xi_{k+1}(s)$$

$$-F_{k\text{ out}}(s) = -Z_2 \Xi_k(s) + (Z_1 + Z_2)\Xi_{k+1}(s)$$

$$Z_1 = \frac{S_o \gamma \operatorname{th}(\delta\gamma)}{s_{ij}^\Psi}, \quad Z_2 = \frac{S_o \gamma}{s_{ij}^\Psi \operatorname{sh}(\delta\gamma)}$$

where $Z_1$, $Z_2$, $s$, $\delta$, $\gamma$, $F_{k\text{ inp}}(s)$, $F_{k\text{ out}}(s)$, $\Xi_k(s)$, $\Xi_{k+1}(s)$ are the resistances of quadripole $k$ piezo layer, the transform parameter, the thickness, the coefficient wave propagation, the Laplace transform of the forces at the input and output ends of $k$ piezo layer, the transforms of the displacements at input and output ends of $k$ piezo layer.

The system of the equations for $k$ piezo layer has the form

$$-F_{k\text{ inp}}(s) = \left(1 + \frac{Z_1}{Z_2}\right) F_{k_{out}}(s) + Z_1 \left(2 + \frac{Z_1}{Z_2}\right) \Xi_{k+1}(s)$$

$$\Xi_k(s) = \frac{1}{Z_1} F_{k\text{ out}}(s) + \left(1 + \frac{Z_1}{Z_2}\right) \Xi_{k+1}(s)$$

This system is founded in the matrix form

$$\begin{bmatrix} -F_{k\text{ inp}}(s) \\ \Xi_k(s) \end{bmatrix} = [M] \begin{bmatrix} F_{k\text{ out}}(s) \\ \Xi_{k+1}(s) \end{bmatrix}$$

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

$$m_{11} = m_{22} = 1 + \frac{Z_1}{Z_2} = \operatorname{ch}(\delta\gamma), \quad m_{12} = Z_1\left(2 + \frac{Z_1}{Z_1}\right) = Z_0 \operatorname{sh}(\delta\gamma)$$

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

The equation of forces at the boundary between two layers is obtained in the form

$$F_{k\text{ out}}(s) = -F_{k+1\text{ inp}}(s)$$

For a multi-layer electro elastic drive with $n$ layers and $l$ length its system has the matrix form

$$\begin{bmatrix}-F_{1\,\mathrm{inp}}(s)\\ \Xi_1(s)\end{bmatrix}=[M]^n\begin{bmatrix}F_{n\,\mathrm{out}}(s)\\ \Xi_{n+1}(s)\end{bmatrix}$$

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

then

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

The equations of forces a multi-layer drive we have in the form

at $x=0,\ T_j(0,s)S_0=F_1(s)+M_1s^2\Xi_1(s)$

at $x=l,\ T_j(l,s)S_0=-F_2(s)-M_2s^2\Xi_2(s)$

The transform of its force causes deformation has the equation in the form

$$F(s)=\frac{v_{mi}S_0\psi_m(s)}{s_{ij}^{\psi}}$$

Then the parametric model and scheme on Figure 1 of a multi-layer electro elastic drive are obtained in the form

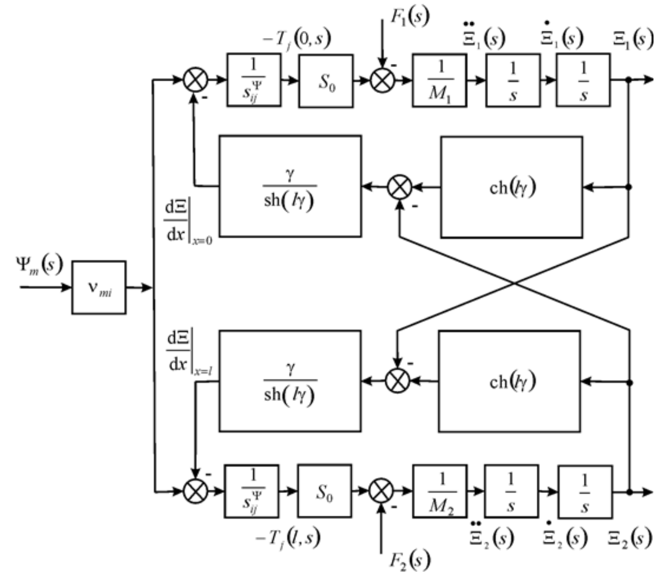

**Figure 1** Parametric scheme multi layer electro elastic drive.

$$\Xi_1(s)=\left(1/\left(M_1s^2\right)\right)\left\{-F_1(s)+\left(1/\chi_{ij}^{\psi}\right)\begin{bmatrix}v_{mi}\psi_m(s)-(\gamma/\mathrm{sh}(l\gamma))\times\\ \times\left(\mathrm{ch}(l\gamma)\Xi_1(s)-\Xi_2(s)\right)\end{bmatrix}\right\}$$

$$\Xi_2(s)=\left(1/\left(M_2s^2\right)\right)\left\{-F_2(s)+\left(1/\chi_{ij}^{\psi}\right)\begin{bmatrix}v_{mi}\psi_m(s)-(\gamma/\mathrm{sh}(l\gamma))\times\\ \times\left(\mathrm{ch}(l\gamma)\Xi_2(s)-\Xi_1(s)\right)\end{bmatrix}\right\}$$

here $v_{mi}=\begin{cases}d_{33},\,d_{31},\,d_{15}\\ g_{33},\,g_{31},\,g_{15}\end{cases}$, $\Psi_m=\begin{cases}E_3,E_1\\ D_3,D_1\end{cases}$, $s_{ij}^{\psi}=\begin{cases}s_{33}^E & s_{11}^E & s_{55}^E\\ s_{33}^D & s_{11}^D & s_{55}^D\end{cases}$,

$c^{\Psi}=\begin{cases}c^E\\ c^D\end{cases}$, $\gamma=\begin{cases}\gamma^E\\ \gamma^E\end{cases}$, $\chi_{ij}^{\psi}=s_{ij}^{\psi}/S_0$.

The matrix function of a multi-layer drive has the form

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

then

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

$$[\Xi(s)]=\begin{bmatrix}\Xi_1(s)\\ \Xi_2(s)\end{bmatrix},\ [P(s)]=\begin{bmatrix}\Psi_m(s)\\ F_1(s)\\ F_2(s)\end{bmatrix}$$

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

The functions of a multi-layer drive are determined

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

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

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

$$W_{21}(s)=\Xi_2(s)/\psi_m(s)=-v_{ij}^{\psi}M_1\chi_{ij}^{\psi}s^2+\gamma\mathrm{th}(l\gamma/2)/A_{ij}$$

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

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

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

The function of the multi-layer longitudinal piezo drive with one fixed face is determined at the elastic-inertial load and the control of voltage in the form

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

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

Its transient response has the form

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

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

For the multi-layer longitudinal PZT drive at $U_m$ =60 V, $d_{33}$ = $4\cdot10^{-10}$ m/V, $n$ = 8, $M$ = 1 kg, $C_{33}^E$ = $5.8\cdot10^7$ N/m, $C_e$ = $0.6\cdot10^7$ N/m its parameters $\xi_m$ = 174 nm and $T_t$ = $1.25\cdot10^{-4}$ s are obtained with error 10%.

## Discussion

We have the parametric model and scheme of a multi-layer electro elastic drive of robotics by using of mathematical physics method. The system of equations for *T*-form quadripole of *k* piezo layer is used. For a multi-layer electro elastic drive its system has the matrix form. By using the equations of forces on ends of a multi-layer drive and the equation of force causes deformation its parametric model and scheme, functions are determined.

## Conclusion

A multi-layer electro elastic drive of robotics is used in adaptive optics, scanning microscopy, micro surgery, interferometry, nanotechnology, nano pump, nano stabilization, compensation of deformations. The parameters of the multi-layer longitudinal PZT drive at the control of voltage are obtained.

The characteristics in of the multi-layer piezo drive are obtained by applied of mathematical physics method. Future works are planned to explore the multi-layer piezo drive for adaptive optics of compound telescope.

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## Conflicts of interest

Author declares that there is no conflict of interest.

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