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Calculation Structural Model of Engine for Nanobiomedicine

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Abstract

The structural model of the electroelastic engine for nanobiomedicine is determined. The structural scheme of the engine is constructed. For the mechatronics systems with the elecroelastic engine its deformations are obtained.

Keywords: structural model and scheme; electro elastic engine; piezo engine; deformation; matrix equation; nanobiomedicine

Introduction

The electro elastic engine based on the piezoelectric or electrostriction effect is used in the mechatronics systems in Nano biomedicine. The piezo engine is the piezo mechanical device, based on the reverse piezo effect, for the actuation of the mechanisms and the systems or for its management, for the convention the electrical signals into the mechanical movement or the force [1-6]. The energy conversion for the structural schema of an electro elastic engine is visibility with difference from the conversion for Cady's and Mason's electrical circuits of a piezo transducer [7-9].

Consider building the structural model of the piezo engine, representing the system of equations, which describes the structure scheme and conversion the electric energy into mechanical energy and the corresponding displacements and forces at its the ends. The structural scheme and transfer functions of the piezo engine are obtained from its structural model [4-15]. The piezo engine is used for precise adjustment, compensation of the temperature and gravitational deformations in scanning microscopy [16-21].

Structural model and scheme of engine

In the electro elastic engine there are six stress components T_1, T_2, T_3, T_4, T_5, T_6, where the components T_1 - T_3 are related to extension-compression stresses and the components T_4 - T_6 are associated to shear stresses. The deformation of the electroelastic engine is corresponded to its stressed state.

The matrix state equations [8, 11-14] for the electric and elastic variables of the piezo engine have the form

$$(D)=(d)(T)+\left(\varepsilon^{T}\right)(E)$$

$$(S)=\left(s^{E}\right)(T)+(d)^{t}(E)$$

where the first equation describes the direct piezo effect, and the second equation declares the inverse piezo effect, (D) is the column matrix of the electric induction along the coordinate axes; (d) is the matrix of the piezo modules; (T) is the column matrix of the mechanical stresses; $\left(\varepsilon^{T}\right)$ is the matrix of the dielectric constants for $T=\text{const}$; (E) is the column matrix of the electric field strength along the coordinate axes; (S) is the column matrix of the relative deformations; $\left(s^{E}\right)$ is the matrix of the elastic compliance for $E=\text{const}$; $(d)^{t}$ is the transposed matrix of the piezo modules.

In the polarized piezo ceramics from lead zirconate titanate PZT for the piezo engine there are five independent components s_{11}^{E}, s_{12}^{E}, s_{13}^{E}, s_{33}^{E}, s_{55}^{E} in the elastic compliance matrix, three independent components d_{33}, d_{31}, d_{15} in the matrix of the piezo modules and three independent components $\varepsilon_{11}^{\mathrm{T}}$, $\varepsilon_{22}^{\mathrm{T}}$, $\varepsilon_{33}^{\mathrm{T}}$ in the matrix of the dielectric constants.

For the piezo engine from the piezo ceramics PZT the matrix of the matrix of the piezo modules has the form

$$(d)=\begin{pmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{pmatrix}$$

The matrix of the dielectric constants has the form

$$\boldsymbol{\varepsilon}^T=\begin{pmatrix} \varepsilon_{11}^{\mathrm{T}} & 0 & 0 \\ 0 & \varepsilon_{22}^{\mathrm{T}} & 0 \\ 0 & 0 & \varepsilon_{33}^{\mathrm{T}} \end{pmatrix}$$

For the piezo engine from the piezo ceramics PZT the matrix of the elastic compliances has the form

$$(s^E)=\begin{pmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{12}^E & s_{11}^E & s_{13}^E & 0 & 0 & 0 \\ s_{13}^E & s_{13}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{55}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(s_{11}^E-s_{12}^E) \end{pmatrix}$$

The transposed matrix of the piezo modules has the form

$$(d)^t=\begin{pmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Let us consider the deformations of the piezo engine at the longitudinal, transverse and shift piezo effects are shown on Figure 1. The piezo engine for the longitudinal piezoeffect has the parameters: δ is thickness, S_0 is the area, *P* is the direction of the polarization axis 3. [8, 11-14] has the form:

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

where $S_3=\partial\xi/\partial x$ is the relative displacement of the cross section of the piezo engine, d_{33} is the piezo module for the longitudinal piezo effect, $E_3=U/\delta$ is the electric field strength, U is the voltage between the electrodes of piezo engine, s_{33}^E is the elastic compliance along axis 3, and T_3 is the mechanical stress along axis 3.

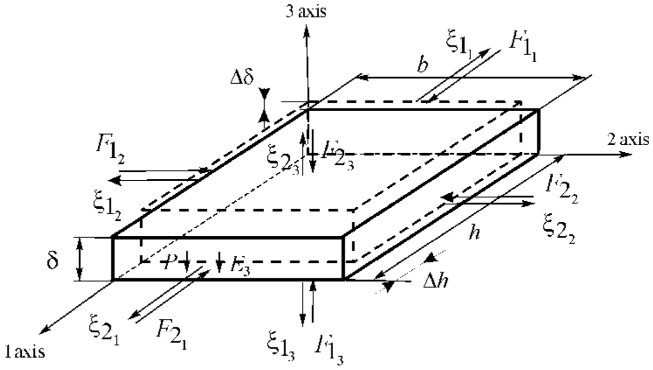

Figure 1. *Deformations of piezo engine.*

For constructing the structural model of the piezo engine, let us solve simultaneously the Laplace transform of the wave equation, the equation of the inverse longitudinal piezo effect, the equation of the forces acting on the faces of the piezo engine. From the wave equation with using Laplace transform is obtained the linear ordinary second-order differential equation with the parameter *s* for calculation the structural model of the piezo engine for nanotechnology and nanobiomedicine [11-45].

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

where $\Xi(x,s)$ is the Laplace transform of the displacement of the section of the piezo engine, *x* is the coordinate, s is the operator, $\gamma=s/c^E+\alpha$ is the propagation coefficient, c^E is the sound speed for $E=\mathrm{const}$, α is the damping coefficient of the wave. The solution the linear ordinary second-order differential equation has form of the function

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

Taking into account the designations

$$\Xi(0,s)=\Xi_1(s) \text{ for } x=0$$

$$\Xi(\delta,s)=\Xi_1(s) \text{ for } x=\delta$$

The coefficients *C* and *B* have form

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

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

The solution the differential equation has form

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

The equations for the Laplace transform of the forces on the faces of the piezo engine have form

$$T_3(0,s)S_0=F_1(s)+M_1s^2\Xi_1(s) \text{ for } x=0$$

$$T_3(\delta,s)S_0=-F_2(s)-M_2p^2\Xi_1(s) \text{ for } x=\delta$$

Where F_1 and F_2 are the external forcse applied to the faces 1 a 2 of the piezo engine, M_1 and M_2 are the masses.

The system of the equations the form the Laplace transforms of the mechanical stresses on the faces 1 and 2 of the piezo engine at $x=0$ and $x=\delta$ has the form

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

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

The system of equations for the structural model of the piezo engine for longitudinal piezo effect has the form

$$\Xi_1(s)=\left[1/\left(M_1s^2\right)\right]\left\{-F_1(s)+\left(1/\chi_{33}^E\right)\left[\begin{array}{l}d_{33}E_3(s)-[\gamma/\mathrm{sh}(\delta\gamma)]\\ \times[\mathrm{ch}(\delta\gamma)\Xi_1(s)-\Xi_2(s)]\end{array}\right]\right\}$$

$$\Xi_2(s)=\left[1/\left(M_2s^2\right)\right]\left\{-F_2(s)+\left(1/\chi_{33}^E\right)\left[\begin{array}{l}d_{33}E_3(s)-[\gamma/\mathrm{sh}(\delta\gamma)]\\ \times[\mathrm{ch}(\delta\gamma)\Xi_2(s)-\Xi_1(s)]\end{array}\right]\right\}$$

Where $\chi_{33}^E=s_{33}^E/S_0$. In general the system of the equations the transform of Laplace for stresses acting on two faces electro elastic engine has the form

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

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

In general the system of the equations for the structural model and the structural scheme on Figure 2 of the electro elastic engine has the form

$$\Xi_1(s)=\left[1/\left(M_1s^2\right)\right]\left\{-F_1(s)+\left(1/\chi_{ij}^\Psi\right)\left[\begin{array}{l}d_{mi}\Psi_m(s)-[\gamma/\mathrm{sh}(l\gamma)]\\ \times[\mathrm{ch}(l\gamma)\Xi_1(s)-\Xi_2(s)]\end{array}\right]\right\}$$

$$\Xi_2(s)=\left[1/\left(M_2s^2\right)\right]\left\{-F_2(s)+\left(1/\chi_{ij}^\Psi\right)\left[\begin{array}{l}d_{mi}\Psi_m(s)-[\gamma/\mathrm{sh}(l\gamma)]\\ \times[\mathrm{ch}(l\gamma)\Xi_2(s)-\Xi_1(s)]\end{array}\right]\right\}$$

where $\chi_{ij}^\Psi=s_{ij}^\Psi/S_0$, $v_{mi}=\left\{\begin{array}{l}d_{33},d_{31},d_{15}\\ g_{33},g_{31},g_{15}\end{array}\right.$, $\Psi_m=\left\{\begin{array}{l}E_3,E_1\\ D_3,D_1\end{array}\right.$, $s_{ij}^\Psi=\left\{\begin{array}{l}s_{33}^E,s_{11}^E,s_{55}^E\\ s_{33}^D,s_{11}^D,s_{55}^D\end{array}\right.$, $l=\{\delta,h,b$, $\gamma=\{\gamma^E,\gamma^D$, $c^\Psi=\{c^E,c^D$, $\chi_{ij}^\Psi=s_{ij}^\Psi/S_0$, and Ψ is the control parameter for the electro elastic engine in the form E for voltage control and D for current control, l is the is the length of the engine.

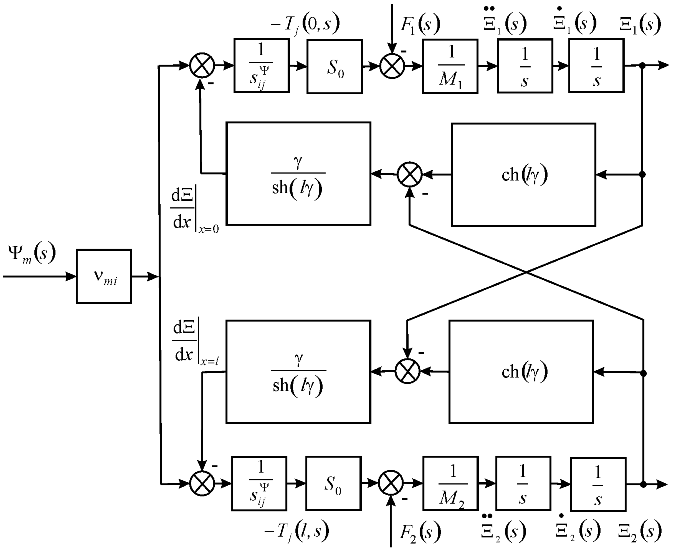

Figure 2. *Structural scheme of electro elastic engine for nanobiomedicine*

This structural scheme of the electroelastic engine is used for calculation the deformations of the electroelastic engine in nanobiomedicine instead Cady's and Mason's electrical equivalent circuits

Displacements of engine

From the structural model on Figure 2 the matrix equation the displacements of the electroelastic engine has the form

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

From the matrix equation the displacements of the electroelastic engine at the inertial load the steady-state the displacements of the faces 1 and 2 for time $t \to \infty$ have the form

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

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

The steady-state the displacements of the faces 1 and 2 for the longitudinal piezo engine have the form

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

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

At d_{33} = 4·10^{-10} m/V, U = 250 V, M_1 = 1 kg and M_2 = 4 kg the static displacements of the faces of the longitudinal piezo engine from piezo ceramics PZT are obtained $\xi_1(\infty)$ = 80 nm, $\xi_2(\infty)$ = 20 nm, $\xi_1(\infty)+\xi_2(\infty)$ = 100 nm. Theoretical and practical displacements of the piezo engine are coincidences with an error of 10%.

Conclusion

The system of the equations for the structural model of the electroelastic engine is obtained. The structural model, the decision of wave equation, the structural scheme, the transfer functions of the electroelastic engine are determined by using the Laplace transform. The structural schemes and the transfer functions of the piezo engine for the transverse, longitudinal, shift piezo effects are obtained from the structural model of the piezo engine.

Using the Laplace transform of the wave equation, the equation of the piezo effect and taking into account the features of the deformations along the coordinate axes, the structural model and the structural scheme of the piezo engine are constructed for the mechatronics systems in nanobiomedicine. The transfer functions of the electroelastic engine in the matrix form are used for the calculation of the mechatronics systems.

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