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MATHEMATICAL MODELING. MATHEMATICS

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ. МАТЕМАТИКА

UDC 539.3

FORCED VIBRATIONS AND DISSIPATIVE HEATING OF THREE-DIMENSIONAL PIEZOELECTRIC PRISM

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Summary. *Prismatic passive and piezoactive nonelastic bodies are used wide-ly in present – day technics. Under harmonic loading the electromechanical energy in these bodies is turning in thermal energy and the body temperature is increasing. This temperature is named the temperature of dissipative heating. If the temperature is equal to degradation point of active material, the structure element is losing the functional role. For active material the degradation point is equal Curie point. For investigation of dissipative heating of nonelastic elements it is necessary to use coupling theory of thermoelectroviscoelastisity.*

In this paper the formulation of tree-dimensional coupling problem on the forced vibrations and dissipative heating of nonelastic piezoelectric prism under harmonic electric loading is given. Nonelastic behavior of material is modeling of complex characteristics. Dissipative heating in energy equation is bringed. It is proposed that material characteristics don't depend on the temperature. Then the problem is reduced to solution of two problems: problem of electroelastisity and problem of heat conduc-tivity with known heat source. Solutions of problems electroelasticity and heat conductivity are found by finite element method.

By these approaches the three-dimensional problem on forced vibrations and dissipative heating of piezoelectric prism body under harmonic electric loading is soluted. Dependence of vibration amplitude and temperature on frequency is calculated.

Key words*: forced vibrations, dissipative heating, piezoelectric, three-dimensional prism*.

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Statement of the problem. One of the most common modes of elements operation in the designs of modern technology for various purposes, including prismatic ones from piezoelectric material, is their forced oscillations. Each passive (without piezoelectric effect) or active material in one way or another exhibits inelastic properties. For prolonged forced oscillations, inelastic behavior the material results in the temperature increase due to hysteresis losses, to the so-called temperature of dissipative warming up. It can significantly affect the oscillatory processes in inelastic piezoelectric bodies and even their thermal destruction, which means reaching the temperature of dissipative warming of such a level when the functional capacity of the inelastic element of the design is because of reaching Curie point temperature

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of the material active where it loses the piezoelectric effect. Therefore, the investigation of forced oscillations of prismatic inelastic piezoelectric bodies with their harmonic electromechanical loading is important problem of thermoelectromechanics.

Analysis of the available investigation results. The main achievements in the investigation of forced oscillations and dissipative warming of thin-walled and transparent elements of constructions made of passive and piezo-active materials were obtained by the staff of the Institute of Mechanics of the National Academy of Sciences of Ukraine. The results of these studies are published in many articles and monographs by these staff [1 − 10] providing detailed analysis of scientific achievements on these issues. However, investigations of forced oscillations and dissipative heating of prismatic inelastic piezoelectric bodies with harmonic electro-mechanical loading in spatial formulation are not presented in modern literature, although they are widely used in various fields of modern technology.

The objective of the paper investigate the influence of electromechanical and temperate fields connection on the thermoelectromechanical behavior of inelastic piezoelectric prismatic bodies under the action of electromechanical load harmonized in time. The main attention is focused on the construction of amplitude and temperature-frequency characteristics.

Statement of the problem and its solution. Three-dimensional non-elastic prismatic piezoelectric body, which yields harmonic time difference potential is considered. The interaction of mechanical, electrical and temperature fields is taken into account. The body temperature rises as the result of hysteresis losses in the inelastic material. The simulation of forced harmonic oscillations uses the concept of complex characteristics, according to which the defining equations have the same form as the defining equations for the elastic material and the only difference is that their actual characteristics are replaced by complex ones. The dissipative function in the energy equation is equal to the averaged over the power cycle. It is believed that the characteristics of the material are not temperature dependent. In this case, the problem is divided into two separate tasks. The first one is to solve the problem of electromechanics. From this solution the dissipative function is found. The second task is to solve the heat equation with the heat source, which coincides with the dissipative function. To solve these tasks, the finite element method [9] is used.

The dynamic task of electromechanics is reduced to the solution of the variational problem for the functional

$$\begin{aligned}
\text{э} = \frac{1}{2}\iiint\limits_{(V)} & [C_{11}\varepsilon_{xx}^2 + 2C_{12}\varepsilon_{xx}\varepsilon_{yy} + 2C_{13}\varepsilon_{xx}\varepsilon_{zz} + C_{11}\varepsilon_{yy}^2 + 2C_{13}\varepsilon_{yy}\varepsilon_{zz} + \\
& + C_{33}\varepsilon_{zz}^2 + 2(C_{11} - C_{12})\varepsilon_{xy}^2 + 4C_{44}\varepsilon_{xz}^2 + 4C_{44}\varepsilon_{zy}^2 - 2e_{13}\varepsilon_{xx}\varepsilon_{zz} - 2e_{13}\varepsilon_{yy}\varepsilon_{zz} + \\
& - 2e_{13}\varepsilon_{yy}E_z - 4e_{15}\varepsilon_{xz}E_x - 4e_{15}\varepsilon_{yz}E_y - \gamma_{11}E_x^2 - \gamma_{11}E_y^2 - \gamma_{33}E_z^2 - \\
& - \rho\omega^2\left(w^2 + u^2 + v^2\right)]dxdydz - \\
& - \int\limits_{S_0}\left(p_{nz}w + p_{nx}u + p_{ny}v - o^2\varphi\right)dS.
\end{aligned} \qquad (1)$$

Hereinafter, the designation of work [1] is used.

To solve the variation equation $\delta\,\text{э} = 0$, 24-node spatial isoparametric elements with quadratic approximation of components of the displacement vector and the electric potential within the element are used. The decoded coordinate system (x, y, z) is used as the global coordinate system combining all elements. The normalized coordinate system (ξ, η, ς). is used as local coordinate system, in which the approximating functions are determined on the element and the integration is carried out.

Let us divide the area occupied by the body N, into M spatial elements by the node points. We assume that the displacement and electric potential within the element limits are approximated by expressions

$$W = \sum_{i=1}^{24} K_i W_i, \quad U = \sum_{i=1}^{24} K_i U_i, \quad V = \sum_{i=1}^{24} K_i V_i, \varphi = \sum_{i=1}^{24} K_i \varphi_i, \tag{2}$$

where W_i, U_i, V_i, φ_i are values of nodes displacement values and electrical potential, K_i are combinations of algebraic polynomials:

$$\begin{aligned}
&K_1 = L_1 H_1; \quad K_2 = L_2 H_1; \quad K_3 = L_3 H_1; \quad K_4 = L_4 H_1;\\
&K_5 = L_5 H_1; \quad K_6 = L_6 H_1; \quad K_7 = L_7 H_1; \quad K_8 = L_8 H_1;\\
&K_9 = L_1 H_2; \quad K_{10} = L_2 H_2; \quad K_{11} = L_3 H_2; \quad K_{12} = L_4 H_2;\\
&K_{13} = L_5 H_2; \quad K_{14} = L_6 H_2; \quad K_{15} = L_7 H_2; \quad K_{16} = L_8 H_2;\\
&K_{17} = L_1 H_3; \quad K_{18} = L_2 H_3; \quad K_{19} = L_3 H_3; \quad K_{20} = L_4 H_3;\\
&K_{21} = L_5 H_3; \quad K_{22} = L_6 H_3; \quad K_{23} = L_7 H_3; \quad K_{24} = L_8 H.
\end{aligned} \tag{3}$$

Here

$$\begin{aligned}
&L_1 = \frac{1}{4}(1-\xi)(1-\eta)(-\xi-\eta-1), \quad L_2 = \frac{1}{4}(1+\xi)(1-\eta)(\xi-\eta-1),\\
&L_3 = \frac{1}{4}(1+\xi)(1+\eta)(\xi+\eta+1), \quad L_4 = \frac{1}{4}(1-\xi)(1+\eta)(-\xi+\eta-1),\\
&L_5 = \frac{1}{2}\left(1-\xi^2\right)(1-\eta), \quad L_6 = \frac{1}{2}\left(1-\eta^2\right)(1+\xi),\\
&L_7 = \frac{1}{2}\left(1-\xi^2\right)(1+\eta), \quad L_8 = \frac{1}{2}\left(1-\eta^2\right)(1-\xi)\\
&H_1 = \frac{1}{2}(\varsigma-1)\varsigma, \quad H_2 = \frac{1}{2}(\varsigma+1)\varsigma, H_3 = \left(1-\varsigma^2\right).
\end{aligned} \tag{4}$$

Since isoparametric elements are used, the body may have an arbitrary geometric shape.

The relationship between Cartesian (x,y,z) and local (ξ, η, ς) coordinates is performed by means of dependencies

$$x = \sum_{i=1}^{24} K_i x_i; \quad y = \sum_{i=1}^{24} K_i y_i; z = \sum_{i=1}^{24} K_i z_i,$$

where x_i, y_i, z_i are coordinates of node points.

Partial derivatives while determining the deformations and the electric field strength vector components should be calculated according to ξ, η, θ and then the resulting dependencies are solved with respect to derivatives in Cartesian coordinates:

$$\begin{Bmatrix} \dfrac{\partial u}{\partial \xi} \\ \dfrac{\partial u}{\partial \eta} \\ \dfrac{\partial u}{\partial \varsigma} \end{Bmatrix} = \left\| \begin{matrix} \dfrac{\partial x}{\partial \xi} & \dfrac{\partial y}{\partial \xi} & \dfrac{\partial z}{\partial \xi} \\ \dfrac{\partial x}{\partial \eta} & \dfrac{\partial y}{\partial \eta} & \dfrac{\partial z}{\partial \eta} \\ \dfrac{\partial x}{\partial \varsigma} & \dfrac{\partial y}{\partial \varsigma} & \dfrac{\partial z}{\partial \varsigma} \end{matrix} \right\| \left\| \begin{matrix} \dfrac{\partial u}{\partial x} \\ \dfrac{\partial u}{\partial y} \\ \dfrac{\partial u}{\partial z} \end{matrix} \right\| = J \left\| \begin{matrix} \dfrac{\partial u}{\partial x} \\ \dfrac{\partial u}{\partial y} \\ \dfrac{\partial u}{\partial z} \end{matrix} \right\|, \qquad (5)$$

where $|J|$ is Jacobian.

The solution of equation (5) gives

$$\frac{\partial u}{\partial x} = \frac{\Delta_{11}}{J}, \quad \Delta_{11} = \left\| \begin{matrix} \dfrac{\partial u}{\partial \xi} & \dfrac{\partial y}{\partial \xi} & \dfrac{\partial z}{\partial \xi} \\ \dfrac{\partial u}{\partial \eta} & \dfrac{\partial y}{\partial \eta} & \dfrac{\partial z}{\partial \eta} \\ \dfrac{\partial u}{\partial \varsigma} & \dfrac{\partial y}{\partial \varsigma} & \dfrac{\partial z}{\partial \varsigma} \end{matrix} \right\|. \qquad (6)$$

Similarly we find derivatives $\dfrac{\partial u}{\partial y}, \dfrac{\partial u}{\partial z}$.

Expressions for the tensor components deformation and the electric field strength vector components can be presented in the following form

$$\varepsilon_{xx} = \sum_{i=1}^{24} \Phi_i u_i; \quad \varepsilon_{yy} = \sum_{i=1}^{24} \Psi_i v_i; \quad \varepsilon_{zz} = \sum_{i=1}^{24} F_i w_i;$$

$$\varepsilon_{zy} = \frac{1}{2}\left(\sum_{i=1}^{24} \Psi_i u_i + \sum_{i=1}^{24} \Phi_i v_i \right); \quad \varepsilon_{zz} = \frac{1}{2}\left(\sum_{i=1}^{24} F_i V_i + \sum_{i=1}^{24} \Phi_i W_i \right);$$

$$\varepsilon_{yz} = \frac{1}{2}\left(\sum_{i=1}^{24} F_i v_i + \sum_{i=1}^{24} \Psi_i w_i \right),$$

$$E_x = -\sum_{i=1}^{24} \Phi_i \phi_i; E_y = -\sum_{i=1}^{24} \Psi_i \phi_i, E_z = -\sum_{i=1}^{24} F_i \phi_i.$$

The mechanical loads $\vec{P}$ are also approximated by form functions within each finite element:

$$P_{nz} = \sum_{i=1}^{24} K_i P_{inz}, \quad P_{nr} = \sum_{i=1}^{24} K_i P_{inr}, \quad P_{n\theta} = \sum_{i=1}^{24} K_i P_{in\theta},$$

Substituting the expressions for the deformations and the component of the electric field intensity vector in the functional (1), under the condition of its stationarity, we obtain the system of linear algebraic equations relatively to the node values of the displacement vector components $(w_i,\ u_i,\ v_i,)$ and the electrical potential φ for a single finite element. Expressions for the coefficients of these equations are determined through the complex physical and mechanical characteristics of the viscoelastic piezomaterial and geometric parameters of the body. Summing up the coefficients for all finite elements, we obtain the global system of equations that is solved by the Gaussian method in the complex domain. According to the obtained values of the displacement and electric potential the components o the tensors stress deformation, as well as the components of the electric field tension vectors and electrical induction are determined. Investigation of the thermomechanical behavior of bodies made of viscous-elastic piezoelectric material are reduced to joint solution of the problem of electromechanics and the problem of non-stationary thermal conductivity.

Three-dimensional non-stationary heat conduction problem with the known heat source is also solved by the finite element method on the same grid of finite elements as the task of electromechanics. In this case, the variational formulation of the problem is used, which is equivalent to the statement in differential form:

$$\delta I = 0,$$

where

$$I = \frac{1}{2}\iiint\limits_V \left[\lambda_x \left(\frac{\partial T}{\partial x}\right)^2 + \lambda_y \left(\frac{\partial T}{\partial y}\right)^2 + \lambda_z \left(\frac{\partial T}{\partial z}\right)^2 - 2\rho c_T \frac{\partial T}{\partial t} - 2DT \right] dxdydz - \iint\limits_S \alpha_T \left(\frac{1}{2}T - T_C\right) TdS.$$

Substitution of the derivative from the temperature by time expression

$$\frac{\partial T}{\partial t} = \frac{T(t+\Delta t) - T(t)}{\Delta t}$$

gives the opportunity to implement the implicit scheme for solving the heat conduction problem.

Applying the above described approach, we solve the problem of forced oscillations and dissipative heating of rectangular prism with H=2h_1 + h_0 thickness consisting of the same external piezoelectric viscoelastic layers of h_1 thickness and internal layer of h_0 thickness from passive material. Electrodes are applied on the surface of the piezoelectric layers. Zero potential value is maintained on the internal electrodes. The potential difference $\varphi = \varphi_0 \cos \omega t.$ 3 is applied to the external electrodes. The edges of the plate are hinge rested. The outer layers of the plate are made of piezoceramic PZT-Tc-65 with thick polarization, and the inner layer is made of aluminum. Complete compliance S_{ij}^E, piezoelectric constants d_{ij} and dielectric penetration μ_{ij} for indicated material are given in [9] and have the following meanings:

$$S_{11}^E = (17{,}2 - 0{,}2i)\cdot 10^{-12} m^2/N,\ S_{12}^E = (-5{,}8 + 0{,}1i)\cdot 10^{-12} m^2/N,$$
$$S_{13}^E = (-9{,}1 + 0{,}2i)\cdot 10^{-12} m^2/N,$$
$$S_{33}^E = (18{,}4 - 0{,}4\,\mathrm{i})\cdot 10^{-12} m^2/N,\quad S_{55}^E = (48 - 5{,}6\,\mathrm{i})\cdot 10^{-12} m^2/N,$$
$$d_{33} = (357\ \text{-}14{,}7\mathrm{i})\cdot 10^{-12} s/N,\ d_{31} = (189{,}7\ \text{-}4{,}8\mathrm{i})\cdot 10^{-12} s/N,$$
$$d_{15} = (609\ \text{-}253{,}6\mathrm{i})\cdot 10^{-12} s/N,$$
$$\mu_{11}^E = (20541\text{-}\ 1127\mathrm{i})\cdot 10^{-12} F/m,,\ \mu_{33}^T = (14803\text{-}\ 342\mathrm{i})\cdot 10^{-12} F/m.$$

Complex characteristics C_{ij}, piezomodules e_{ij}, dielectric penetrations μ_{ij}^{T} are determined through characteristics $S_{ij}^{E}, d_{ij}, \mu_{ij}^{T}$ according to the formulas given in [1].

The coefficients of thermal conductivity and material density of the outer layer have the following values: λ = 1,25 W/(*m/K*), ρ = 0,75 $\cdot 10^4$ kg/ m^3.

Calculations are carried out for the plate with sides a = b = 0,1m, total thickness H= 0,02 m and layers thickness h_1 = 0,005 m, h_2 = 0,01 m.

Physical and mechanical properties of the inner layer have the following meanings $E_o = 7{,}3 \cdot 10^{10}\, N/m^2$, ν = 0,34, ρ = 0,27 $\cdot 10^4\, kg/m^3$, λ =210 *W/(m/K)*

The plate is in the heat exchange with the external medium with the temperature $T_c = 20^0 C$. Heat exchange coefficient between the external medium and the plate α_T = 25*W/(m/K)*

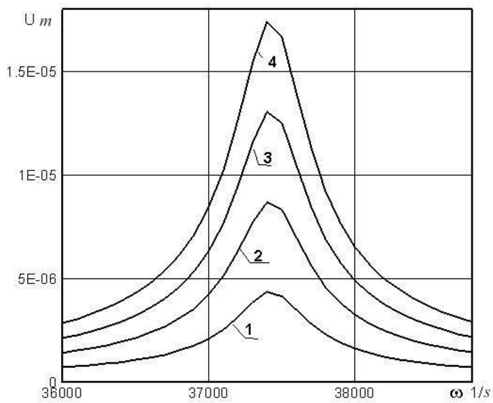

Figure 1. Dependencies of plate' deflect on frequency

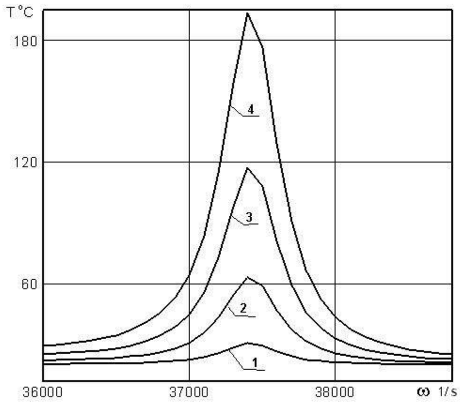

Figure 2. Dependencies of plate' temperature on frequency

Investigation results. The results of calculations are shown in Figures 1, 2, where the dependence of deflection and temperature of the dissipative heating on the frequency for different values of electric load: φ_0 =12V,24V, 36V, 48V (curves 1, 2, 3, 4 relatively). From the graphs presented in these figures, it is evident that these values depend essentially on the value of the summed potential difference and on the frequency. With increasing electric load, the temperature of dissipative heating can reach the critical value at which this temperature reaches Curie point and the material loses its piezoelectric effect. In this case, there is the specific type of thermal fracture, when the structure is not divided into parts, but it stops to perform its functional purpose.

Conclusions. With using conception of the complex characteristics the formulation of three-dimentiol coupling problem on the forced vibrations and dissipative heating of nonelastic piezoelectric prism under harmonic electric loading is given. It is proposed that material characteristics don't depend on the temperature. The problem is reduced to solution of two problems: problem of electroelastisity and problem of heat conductivity with known heat source. Solutions of problems electroelasticity and heat conductivity are found by finite element method.

By these approaches the three-dimensional problem on forced vibrations and dissipative heating of piezoelectric prism body under harmonic electric loading is soluted. Dependence of vibration amplitude and temperature on frequency is calculated.

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УДК 539.3

ВИМУШЕНІ КОЛИВАННЯ І ДИСИПАТИВНИЙ РОЗІГРІВ ТРИВИМІРНОГО ПРИЗМАТИЧНОГО ТІЛА З П'ЄЗОЕЛЕКТРИЧНОГО МАТЕРІАЛУ

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Резюме. *Призматичні тіла з пасивних та п'єзоактивних матеріалів широко використовуються в сучасній техніці. При гармонічному навантаженні електромеханічна енергія в таких тілах перетворюється в теплову енергію і температура тіла підвищується. Ця температура називається температурою дисипативного розігріву. Якщо ця температура дорівнює точці деградації активного матеріалу, елемент конструкції втрачає своє функціональне призначення. Для активного матеріалу точка деградації дорівнює точці Кюрі. Для дослідження дисипативного розігріву необхідно використовувати зв'язану теорію термоелектров'язкопружності. В даній роботі наведено постановку тривимірної зв'язаної задачі про вимушені коливання й дисипативний розігрів непружної п'єзоелектричної призми при гармонічному електричному навантаженні. Непружна поведінка матеріалу моделюється комплексними характеристиками. Наведено дисипативну функцію, яка входить у рівняння енергії. Вважається, що характеристики матеріалу не залежать від температури. Тоді задача зводиться до розв'язування двох задач: задачі електропружності й задачі теплопровідності з відомим джерелом тепла. Розв'язок цих задач знаходиться методом скінчених елементів. Із використанням вказаного підходу розв'язано тривимірну задачу про вимушені коливання й дисипативний розігрів призматичного п'єзоелектричного тіла при гармонічному електричному навантаженні. Розраховано амплітуду – та температурно − частотні характеристики.*

Ключові слова*: вимушені коливання, дисипативний розігрів, п'єзоелектрична тривимірна призма.*

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