MODELING OF DEFORMATION OF CONDUCTING BODIES IN MAGNETIC FIELD

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Annotation: *The interaction of physical fields in a deformable body is especially significant when analyzing the strength and reliability of structural elements functioning under the action of high temperatures, pressures, and strong electromagnetic fields. The need for optimal designs for mechanical engineering has led to the development of a new area of the theory of coupled physical fields, combining the theory of elasticity and the theory of electromagnetism - magnetoelasticity, on the basis of which the problems of motion of an elastic electrically conductive body in a magnetic field are solved. The study of the interaction of electromagnetic fields with an elastic body containing structural inhomogeneities significantly depends on the properties of the material in relation to the electromagnetic field: electrically conductive bodies are equally affected by electric and magnetic fields, dielectrics are predominantly affected by electric fields, and magnetic materials are affected by magnetic fields. The work mathematically models the deformation of conductive bodies under the influence of non-stationary electromagnetic forces and mechanical loads. Numerical results were obtained and electromagnetic effects were analyzed.*

Key words: *deformation, stresses, electromagnetic field.*

An important place in the mechanics of conjugate fields is occupied by the study of the motion of a continuous medium, taking into account electromagnetic effects. When a conducting body moves in a magnetic field or when the magnetic field changes over time, induced currents and the Lorentz ponderomotive forces caused by them arise in the body, which, in turn, is accompanied by deformation of the medium and the appearance of stress waves.

Great scientific interest in the mechanics of coupled fields is caused by practical needs. When creating a number of technical devices and modern structural materials, it is necessary to take into account the effects caused by the interaction of electromagnetic and temperature fields with mechanical fields.

With constant mechanical and geometric parameters of the problem, by changing the electrodynamic parameters it is possible to obtain structural elements with qualitatively new mechanical behavior.

Note that recently materials and nanomaterials with new electromagnetic properties have been created. These materials can be effectively used in various fields of new technology in the development of new technologies.

Assuming that a current-carrying body is acted upon by an external magnetic field, we present the magnetoelasticity equation in the region occupied by the body in the form [3, 4, 5, 7, 8, 9, 10]:

$$rot\ \vec{E} = -\frac{\partial \vec{B}}{\partial t};\ rot\ \vec{H} = \vec{J} + \vec{J}_{cm};\ div\ \vec{B} = 0;\ div\ \vec{D} = 0; \quad (1)$$

$$\rho \frac{\partial \vec{V}}{\partial t} = \rho(\vec{f} + \vec{f}^{\wedge}) + div\ \vec{P} \quad (2)$$

where $\vec{E}$ – electric field strength; $\vec{H}$ – magnetic field strength; $\vec{B}$– magnetic induction; $\vec{D}$– electric induction; $\vec{J}$– electric current density; $\vec{J}_{cm}$– third-party electric current density; ρ– material density; $\vec{f}$– volumetric mechanical force; $\vec{f}^{\wedge}$– Lorentz force; $\vec{V}$ – strain rate; $\hat{\sigma}$– internal stress tensor.

Let us assume that the geometric and mechanical characteristics of the body are such that to describe the deformation process we will use a version of the geometrically nonlinear theory of thin shells in the quadratic approximation.

For the considered case of quadratic nonlinearity [2, 3], we assume that the deformations and shifts are small in comparison with the angles of rotation of the element, and the angles themselves are significantly less than unity.

The elastic properties of the shell material correspond to an orthotropic body, the main directions of elasticity of which coincide with the directions of the corresponding coordinate lines, while the electromagnetic properties of the material are characterized by the tensors of electrical conductivity σ_{ij}, magnetic permeability μ_{ij}, dielectric constant $\varepsilon_{ij}\ (i, j = 1,2,3)$.

In this case, based on crystal physics [2], for the class of conducting orthotropic media with an orthorhombic crystal structure, we assume that the tensors , σ_{ij}, ε_{ij} and μ_{ij} take a diagonal form.

The system of magnetoelasticity equations must be closed by relations connecting the vectors of strength and induction of the electromagnetic field, as well as Ohm's laws, which determine the conduction current density in a moving medium.

If an orthotropic body is linear with respect to magnetic and electrical properties, then the governing equations for the electromagnetic field characteristics and the kinematic equations for electrical conductivity, as well as expressions for Lorentz forces, taking into account the external current $\vec{J}_{cm}$, will be written respectively in the form [4]:

$$\vec{B}=\mu_{ij}\vec{H},\ \vec{D}=\varepsilon_{ij}\vec{E}, \tag{3}$$

$$\vec{J}=\sigma_{ij}\ \Gamma F^{T}F^{-1}\left[\vec{J}_{cm}+\vec{E}+\vec{\upsilon}\times\vec{B}\right], \tag{4}$$

$$\rho\vec{f}^{\wedge}=\Gamma^{-1}F^{-1}\left[\vec{J}_{cm}\times\vec{B}+\sigma_{ij}\left(\vec{E}+\vec{\upsilon}\times\vec{B}\right)\times\vec{B}\right]. \tag{5}$$

Thus, (1), (2) together with relations (3)–(5) constitute a closed system of nonlinear equations of magnetoelasticity of current-carrying orthotropic bodies with orthotropic conducting properties.

We will consider non-ferromagnetic flexible shells of variable thickness along the meridian, which are under the influence of non-stationary electromagnetic and mechanical fields.

Neglecting the influence of polarization and magnetization processes, we assume that an alternating electric current is supplied to the end of the shell from an external source.

It is assumed that the external electric current in an unperturbed state is uniformly distributed over the body (the current density does not depend on the coordinates).

We also assume that regarding the electric field strength and magnetic field strength, the electromagnetic hypotheses are satisfied [1, 5, 6]:

$$\begin{gathered}
E_1=E_1(\alpha,\beta,t);\ E_2=E_2(\alpha,\beta,t);\ E_3=\frac{\partial u_2}{\partial t}B_1-\frac{\partial u_1}{\partial t}B_2;\\
J_1=J_1(\alpha,\beta,t);\ J_2=J_2(\alpha,\beta,t);\ J_3=0; \qquad (6)\\
H_1=\frac{1}{2}\left(H_1^{+}+H_1^{-}\right)+\frac{z}{h}\left(H_1^{+}-H_1^{-}\right);\\
H_2=\frac{1}{2}\left(H_2^{+}+H_2^{-}\right)+\frac{z}{h}\left(H_2^{+}-H_2^{-}\right);\ H_3=H_3(\alpha,\beta,t).
\end{gathered}$$

where $u_i -$ the components of the displacement vector of shell points; $E_i, H_i -$ components of the electric and magnetic field strength vectors of the shell;

J_i – eddy current components; $H_i^{\pm}$ – tangential components of the magnetic field strength on the surfaces of the shell; h – shell thickness.

These assumptions are some electrodynamic analogue of the hypothesis of non-deformable normals and, together with the latter, constitute the hypotheses of magnetoelasticity of thin bodies.

Accepting these hypotheses allows us to reduce the problem of deformation of a three-dimensional body to the problem of deformation of an arbitrarily chosen coordinate surface.

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$$\frac{\partial u}{\partial s}=\frac{1-\nu_s\nu_\theta}{e_s h}N_S-\frac{\nu_\theta\cos\varphi}{r}u-\frac{\nu_\theta\sin\varphi}{r}w-\frac{1}{2}\theta_S^2\ ;$$

$$\frac{\partial w}{\partial s}=-\theta_S\ ;\ \frac{\partial\theta_S}{\partial s}=\frac{12(1-\nu_s\nu_\theta)}{e_s h^3}M_S-\frac{\nu_\theta\cos\varphi}{r}\theta_S\ ;$$

$$\frac{\partial N_S}{\partial s}=\frac{\cos\varphi}{r}\left[\left(\nu_S\frac{e_\theta}{e_S}-1\right)N_S+e_\theta h\left(\frac{\cos\varphi}{r}u+\frac{\sin\varphi}{r}w\right)\right]-$$
$$-P_S+h\,J_{\theta CT}B_\zeta-\sigma_1 h\left[E_\theta B_\zeta+0.5\frac{\partial w}{\partial t}B_\zeta\left(B_S^+ + B_S^-\right)-\frac{\partial u}{\partial t}B_\zeta^2\right]+\rho h\frac{\partial^2 u}{\partial t^2}\ ; \qquad (7)$$

$$\frac{\partial Q_S}{\partial s}=-\frac{\cos\varphi}{r}Q_S+\nu_S\frac{e_\theta}{e_S}\frac{\sin\varphi}{r}N_S+e_\theta h\frac{\sin\varphi}{r}\left(\frac{\cos\varphi}{r}u+\frac{\sin\varphi}{r}w\right)-P_\zeta-$$
$$-0.5h\,J_{\theta CT}\left(B_S^+ + B_S^-\right)-\sigma_3 h\left[-0.5\,E_\theta\left(B_S^+ + B_S^-\right)-0.25\,\frac{\partial w}{\partial t}\left(B_S^+ + B_S^-\right)^2-\right.$$
$$\left.-\frac{1}{12}\frac{\partial w}{\partial t}\left(B_S^+ - B_S^-\right)^2+0.5\frac{\partial u}{\partial t}B_\zeta\left(B_S^+ + B_S^-\right)+\frac{h}{12}\frac{\partial\theta_S}{\partial t}B_\zeta\left(B_S^+ + B_S^-\right)\right]+\rho h\frac{\partial^2 w}{\partial t^2}\ ;$$

$$\frac{\partial M_S}{\partial s}=\frac{\cos\varphi}{r}\left[\left(\nu_S\frac{e_\theta}{e_S}-1\right)M_S+\frac{e_\theta h^3}{12}\frac{\cos\varphi}{r}\theta_S\right]+Q_S+N_S\theta_S-$$

$$-\frac{\sin\varphi}{r}\left(\nu_S\frac{e_\theta}{e_S}M_S+\frac{e_\theta h^3}{12}\frac{\cos\varphi}{r}\theta_S\right)\theta_S+\frac{h^3}{12}\frac{\partial^2\theta_S}{\partial t^2};$$

$$\frac{\partial B_\zeta}{\partial s}=-\sigma_2\mu\left[E_\theta+0.5\frac{\partial w}{\partial t}\left(B_S^+ + B_S^-\right)-\frac{\partial u}{\partial t}B_\zeta\right]+\frac{B_S^+ - B_S^-}{h};$$

$$\frac{\partial E_\theta}{\partial s}=-\frac{\partial B_\zeta}{\partial t}-\frac{\cos\varphi}{r}E_\theta.$$

In relations (7) the notations generally accepted in the theory of shells and the theory of electromagnetoelasticity are used.

The technique for solving the nonlinear problem of magnetoelasticity of current-carrying bodies is based on the sequential use of the Newmark scheme, the quasi-linearization method and the discrete orthogonalization method [2,3,4].

Let us study the behavior of a conductive shell of variable thickness in a magnetic field. Fig.1 shows the distribution of maximum shell stress values.

The results obtained show the influence of anisotropic electrical conductivity, external electric current and external magnetic field on the stress-strain state of current-carrying bodies, and taking into account geometric nonlinearity allows us to significantly clarify the picture of deformation.

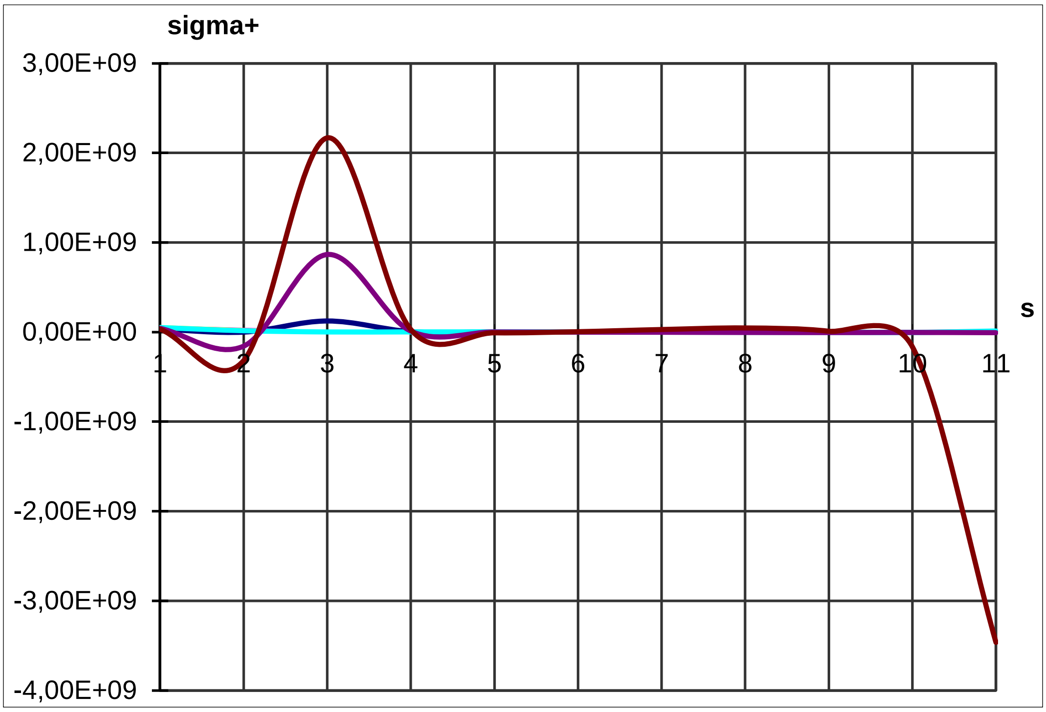

Fig.1 Stress distribution in the shell

The work analyzes the stressed state of a flexible shell under the influence of a time-varying mechanical force and a time-varying external electric current, taking into account mechanical and electromagnetic orthotropy.

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