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INTERACTION BETWEEN MAGNETIC FIELDS AND THIN SHELLS

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Abstract: The motion of an elastic conductive medium in a magnetic field is a complex phenomenon that can have various effects and applications. Boundary value problems of magnetoelasticity are an important tool for the analysis and design of materials and structures that are exposed to magnetic fields and mechanical loads. Solving these problems allows engineers and scientists to optimize the characteristics of these materials and devices for various applications. In this paper, the magnetoelastic deformation of current-carrying shells under the influence of magnetomechanical forces is mathematically modeled. Numerical results are obtained and an analysis of the results is carried out.

Key words: shell, deformation, stress, electromagnetic field, magnetoelasticity.

I. Introduction.

An important place in the mechanics of conjugate fields is occupied by the issues of studying the motion of a continuous medium taking into account electromagnetic effects.

When constructing such models of the mechanics of a deformable solid body, the influence of the electromagnetic field on the thermomechanical behavior of the body is realized through ponderomotive forces and their moments, as well as through sources of additional energy arising from the interaction of the body with an external electromagnetic field [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15].

In general, rigorous mathematical methods play an important role in understanding and analyzing conjugate fields in conductive elements.

These methods continue to develop and find new applications in various fields of science and technology.

Taking electromagnetic effects into account in continuum mechanics is important for understanding the behavior of many materials and devices, such as piezoelectrics, magnetostrictors, and electrorheological fluids.

These materials find applications in a variety of fields, including acoustics, optoelectronics, and robotics.

II. Formulation of the problem. Basic equations.

When exposed to a magnetic field, thin shells can deform, induce stress and current, and achieve dynamic equilibrium under the influence of electromagnetic forces. This interaction can be scientifically explained by combining the principles of electromagnetism and shell mechanics.

1. Key Concepts and Mathematical Representations.

a) Properties of Magnetic Fields.

The fundamental quantities describing magnetic fields are:

Magnetic Field Intensity Vector (H): Describes the strength and direction of the magnetic field.

Magnetic Induction Vector (B): $B = \mu H$, where μ is the magnetic permeability.

Current Density (J) and Magnetic Force: According to Ampere’s law, the relationship between current density and magnetic fields is:

$$\nabla \times H = J. \quad (1)$$

b) Mechanical Model of Thin Shells.

Thin shells are treated as two-dimensional surfaces for mechanical analysis.

The deformation and stresses in shells are characterized by:

Stress Tensor (σ_{ij}): Represents mechanical stresses.

Strain Tensor (ε_{ij}): Measures the deformation of the shell.

Boundary Conditions: Mechanical equilibrium for a thin shell is described by:

$$T_{ij} n_j = f_{i,}, \quad (2)$$

where T_{ij} is the stress, n_j is the normal vector to the shell’s surface, and f_i are external forces.

2. Mechanisms of Interaction Between Magnetic Fields and Shells.

a) Electromagnetic Forces.

Magnetic fields can induce electric currents on the surface of thin shells. These currents interact with the magnetic field, generating electromagnetic forces on the shell’s surface:

$$F_{mag} = J \times B, \quad (3)$$

where:

F_{mag} is the electromagnetic force;

J is the induced surface current density;

B is the magnetic induction vector.

These forces can lead to deformation or dynamic motion of the shell.

b) Thermomagnetic Effects.

Magnetic fields influence the thermal distribution in the shell, leading to thermomagnetic effects. When there is a temperature gradient, the current density is described by:

$$J = \sigma(E + V \times B - \eta \nabla T), \quad (4)$$

where:

∇T is the temperature gradient;

η is the thermoelectric coefficient.

These effects are particularly significant for high-frequency magnetic fields.

c) Deformation Response.

Electromagnetic forces generate mechanical deformation in the shell.

The deformation follows Hooke’s law:

$$\sigma_{ij} = C_{ijkl} \varepsilon_{ij}, \quad (5)$$

where C_{ijkl} is the elasticity modulus matrix.

The deformation of the shell along its surface alters its dynamic response and enhances interaction with the magnetic field.

3. Magnetoelastic Equations.

The mathematical modeling of magnetoelastic behavior involves the following equations:

Electromagnetic Equations:

$$\nabla \times E = -\frac{\partial B}{\partial t},$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}. \quad (6)$$

$$\nabla \cdot B = 0,$$

$$\nabla \cdot D = 0.$$

Mechanical Equilibrium Equation:

$$\nabla \cdot \sigma + \boldsymbol{F}_{mag} = \frac{\rho \partial^2 u}{\partial t^2}, \quad (7)$$

where ρ is the density of the material and u is the displacement vector of the shell.

Magnetic Material Law:

$$B = \mu H,$$

$$J = \sigma E. \quad (8)$$

4. Boundary Conditions for Thin Shells.

The influence of the magnetic field on thin shells is represented through boundary conditions:

Continuity of Current Density:

$$(J \cdot n)_{outer} = (J \cdot n)_{inner}. \quad (9)$$

Continuity of Magnetic Field Intensity:

$$(H \times n)_{outer} = (H \times n)_{inner}. \quad (10)$$

These conditions ensure the physical consistency of the model.

III. Solving the magnetoelasticity problem.

Let us consider a current-carrying microelement of the shell type located in alternating electromagnetic fields. We neglect the processes of polarization and magnetization.

We will relate the middle surface of the shell in the undeformed state to the curvilinear orthogonal coordinate system $\alpha = s, \beta = \theta$, where $s-$ is the length of the arc of the generatrix (meridian), measured from a certain fixed point, θ −is the central angle in a parallel circle.

The coordinate lines $s = const$ and $\theta = const$ are the lines of principal curvature of the middle surface of the shell. Counting the coordinate γ, along the normal to this surface, we will relate the entire shell to the orthogonal spatial coordinate system s, θ, γ.

Following the work [2,3,4,5,6,7,8], we will write the model of magnetoelasticity of a current-carrying microelement in a magnetic field in the following form:

$$\frac{\partial}{\partial s}(rN_s) - \cos\varphi\, N_\theta + \frac{\partial S}{\partial \theta} + \frac{1}{R_s}\frac{\partial H}{\partial \theta} + \frac{r}{R_s}Q_s + r(P_s + \rho F_s^{\wedge}) = r\rho h\frac{\partial^2 u}{\partial t^2};$$

$$\frac{\partial N_\theta}{\partial \theta} + \frac{1}{r}\frac{\partial}{\partial S}(r^2 S) + \frac{\partial}{\partial s}(\sin\varphi\, H) + \frac{\cos\varphi}{R_s}H + + \sin\varphi\, Q_\theta + r\left(P_\theta + \rho F_\theta^{\wedge}\right) = r\rho h\frac{\partial^2 v}{\partial t^2};$$

$$\frac{\partial}{\partial s}(rQ_s) + \frac{\partial Q_\theta}{\partial \theta} - \frac{r}{R_s}N_s - \sin\varphi\, N_\theta + r\left(P_\gamma + \rho F_\gamma^{\wedge}\right) = r\rho h\frac{\partial^2 w}{\partial t^2}; \qquad (11)$$

$$\frac{\partial H}{\partial \theta} + \frac{\partial}{\partial s}(rM_s) - \cos\varphi\, M_\theta - rQ_s - r\left(N_s - \frac{\sin\varphi}{r}M_\theta\right)v_s - rSv_\theta = 0;$$

$$\frac{1}{r}\frac{\partial}{\partial S}(r^2 H) + \frac{\partial M_\theta}{\partial \theta} - rQ_\theta - r\left(N_\theta - \frac{1}{R_s}M_s\right)v_\theta - rSv_s = 0;$$

$$-\frac{\partial B_\gamma}{\partial t} = \frac{1}{r}\left(\frac{\partial(rE_\theta)}{\partial s} - \frac{1}{r}\frac{\partial E_s}{\partial \theta}\right);$$

$$\sigma\left[E_s - \frac{\partial v}{\partial t}B_\gamma - 0{,}5\frac{\partial w}{\partial t}(B_\theta^+ + B_\theta^-)\right] = \frac{1}{r}\frac{\partial H_\gamma}{\partial \theta} + \frac{H_\theta^+ - H_\theta^-}{h};$$

$$\sigma\left[E_\theta - \frac{\partial u}{\partial t}B_\gamma + 0{,}5\frac{\partial w}{\partial t}(B_\theta^+ + B_\theta^-)\right] = -\frac{\partial H_\gamma}{\partial s} + \frac{H_\theta^+ - H_\theta^-}{h};$$

Components of the Lorentz force:

$$\rho F_s^{\wedge} = hJ_\theta B_\gamma + \sigma h E_\theta B_\gamma + \sigma h\left\{0{,}5\frac{\partial w}{\partial t}(B_s^+ + B_s^-)B_\gamma - -\frac{\partial u}{\partial t}B_\gamma^2 - \frac{\partial u}{\partial t}\left[0{,}25(B_\theta^+ + B_\theta^-)^2 + \frac{1}{12}(B_\theta^+ + B_\theta^-)^2\right] + + \frac{\partial v}{\partial t}\left[0{,}25(B_s^+ + B_s^-)(B_\theta^+ + B_\theta^-) + \frac{1}{12}(B_s^+ - B_s^-)(B_\theta^+ - B_\theta^-)\right]\right\};$$

$$\rho F_\theta^{\wedge} = -hJ_s B_\gamma - \frac{h}{r\mu}\frac{\partial B_\gamma}{\partial \theta}B_\gamma + +\sigma h\left\{\frac{\partial u}{\partial t}\left[0{,}25(B_s^+ + B_s^-)(B_\theta^+ + B_\theta^-) + \frac{1}{12}(B_s^+ - B_s^-)(B_\theta^+ - B_\theta^-)\right] - -\frac{\partial v}{\partial t}\left[0{,}25(B_\theta^+ + B_\theta^-)^2 + \frac{1}{12}(B_\theta^+ - B_\theta^-)^2\right]\right. - \frac{B_\theta^+ - B_\theta^-}{\mu}B_\gamma; \qquad (12)$$

$$\rho F_\gamma^{\wedge} = 0{,}5h[J_s(B_\theta^+ + B_\theta^-) - J_\theta(B_s^+ + B_s^-)] + \frac{h}{2r\mu}\frac{\partial B_\gamma}{\partial \theta}(B_\theta^+ + B_\theta^-) - -0{,}5\sigma h E_\theta(B_s^+ + B_s^-) + \sigma h\left\{0{,}5\frac{\partial u}{\partial t}(B_s^+ + B_s^-)B_\gamma - \frac{\partial w}{\partial t}\left[0{,}25(B_s^+ + B_s^-)^2 + + \frac{1}{12}(B_\theta^+ - B_\theta^-)^2 + \frac{1}{12}(B_s^+ - B_s^-)^2\right]\right\} + \frac{(B_\theta^+)^2 - (B_\theta^-)^2}{\mu}.$$

In relations (11) the notations generally accepted in the theory of shells and the theory of electromagnetic elasticity are used.

The method for solving the nonlinear problem of magnetoelasticity of current-carrying bodies is based on the consistent use of the Newmark scheme, the quasi-linearization method and the discrete orthogonalization method [1,2,3,4,5,6,7].

IV.Analysis of numerical results.

As an example, we consider the nonlinear behavior of current-carrying conical shell of variable thickness.

The external electric current in the unperturbed state is uniformly distributed over the shell, i.e. the density of the external current does not depend on the coordinates.

In this case, the shell is subject to a combined load consisting of the Lorentz ponderomotive force and mechanical force.

We will conduct a study of the stress-strain state of flexible current-carrying shells of variable thickness with different types of contour fastening.

The problem for a shell of variable thickness is calculated with different types of shell fastening (2 options).

Boundary conditions:

1. $s = s_0 = 0{:}\quad u = 0,\ w = 0,\ M_s = 0,\ B_\gamma = 0{,}3\ sin\omega t,$

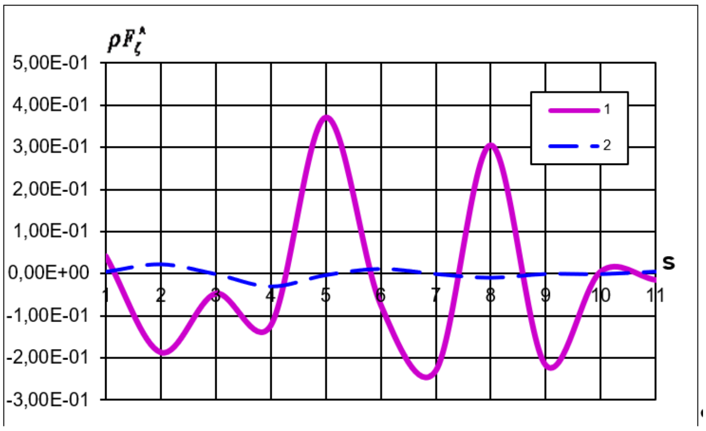
$s = s_N = 0{,}05m{:}\quad u = 0,\qquad w = 0,$

$M_s = 0,\ B_\gamma = 0.$

2. $s = s_0 = 0{:}\ u = 0, Q_s = 0, M_s = 0, E_\theta = -0.5\dfrac{\partial w}{\partial t}(B_s^+ + B_s^-) + \dfrac{\partial u}{\partial t},$

$s = s_N = 0{,}05\ m{:}\quad u = 0,\ w = 0,\ M_s = 0, E_\theta = 0.$

Curves (1,2) in Figure 1 show the distribution of the normal components of the Lorentz force for the corresponding types of boundary conditions 1-2.



1, 2 - correspond to boundary conditions (1-2).

Fig. 1. Distribution $\rho F_\zeta^\wedge$ by s at time $t = 1 \cdot 10^{-3}\, sek$.

As can be seen from the graphs, the distribution of the Lorentz force differs qualitatively and quantitatively depending on the boundary conditions at different times.

Their maximum values arise in different sections of the shell in the presence and absence of magnetic induction and electric field strength depending on the fixing of the edges.

V. Conclusion.

The interaction between magnetic fields and thin shells involves complex physical processes that are scientifically described through mathematical modeling. This interaction manifests as electromagnetic forces, thermomagnetic effects, and mechanical deformations. Magnetoelastic analysis enables the prediction and optimization of the dynamic behavior of shells under magnetic field influence. This understanding is vital for designing advanced devices and systems in engineering and technology. The paper analyzes the stress state of a flexible shell under the action of a time-varying mechanical force and a time-varying external electric current, taking into account geometric nonlinearity. The magnetoelastic nonlinear problem for the shell is considered in a related form. Numerical results are obtained and the stress-strain state is analyzed.

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