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REVIEWS

Scientific and Technical Basis of Application of Nanostructured Materials Science and Nanoelectronics in Systems of Electromechanical Energy Converters for Special Purposes

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Abstract—We consider the current state of a completely new area of science; microsystem electromechanics. The wide spectra of its practical applications and prospects for further development are analyzed. We discuss in detail two main directions of creating micro- and nanoelectromechanical converters as basic elements of microsystem electromechanics: “top down” and “down top.” We also describe the main technological methods in constructing basic functional elements of microsystem electromechanics, areas of their application in traditional and new technologies (information and computer technologies, medicine, aerospace, rocket and artillery systems, etc.). At the same time, we discuss some key issues of generalized physical and mathematical modeling of microelectromechanical and nanoelectromechanical systems (MEMS and NEMS). A new generalized approach is proposed to study dynamic and energy characteristics of MEMS and NEMS as complex dynamic systems with binary conjugate subsystems. Based on proposed theoretical principles and models, the possibilities of studying electrophysical characteristics of biological nanostructures have been considered.

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INTRODUCTION

Following the general trends of world scientific technical progress, modern electromechanical science is developing in two main directions. Its progress is based on the maximum use of the latest achievements of classical mechanics and electromechanics, semiconductor physics, atomic physics, thermodynamics, low- and high-temperature superconductivity physics, energetics, nanostructured materials science and nanoelectronics, cybernetics, etc.

At present, both in the practice of electrical engineering, and in the field of modeling and computer-aided design of electromechanical energy converters (EMECs) of energy, many problems are solved related to the improvement of their energy characteristics and mass-dimensional parameters, the creation of new types of EMECs and their systems. Along with traditional electrical engineering, which is the starting point for revolutionary changes in the 20th century, special-purpose electrical engineering in the areas of electrical power engineering, transport, home appliances, etc., is being intensively developed. The role of electromechanics has greatly increased in the renewable energy industry, in promising aerospace engineering, in high-speed transport with magnetic levitation in new systems of weapons, etc. [1–3].

In the field of modern electromechanics, along with microelectronics, computer technology, telecommunication systems, etc., the need for miniaturization and superminiaturization of functional elements of EMECs is most obvious.

In scientific literature, modern electromechanical science is subdivided into macrosystem electromechanics and microsystem electromechanics. The second of these areas is the most important branch of modern microsystem technology (MST) [4].

Contemporary macrosystem electromechanics includes EMECs of classical and special destination with small, medium, and large power, from micromachines with power less than 1 kW, which are the basis of technological automation process, up to the most powerful electrical machines (hydro- and turbogenerators for power generation systems).

The basic objects of modern research microsystem electromechanics are microminiature EMECs and their systems (microminiature electromechanical systems (MEMS)), and nanoelectromechanical EMECs

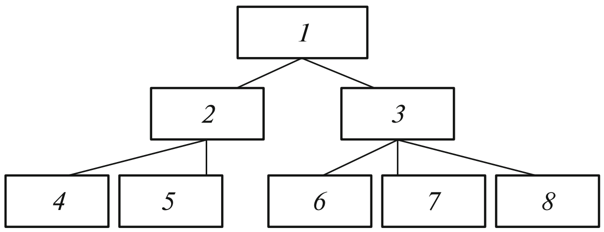

Fig. 1. Classification of EMECs by energy and mass-size parameters: modern electromechanics (*1*), microsystem electromechanics (*2*), macrosystem electromechanics (*3*), nonoelectromechanics (*4*), microminiature electromechanics (*5*), and microelectromechanics (*6*), electromechanics in middle power ranges (*7*), large-scale electrical engineering (*8*).

and their systems (nanoelectromechanical systems (NEMS)) (Fig. 1) [5–7].

CURRENT STATE AND PROSPECTS FOR THE DEVELOPMENT OF MICROSYSTEM ELECTROMECHANICS

The emergence of a modern microsystem electromechanics is associated with the next great achievements in the development of technical and technological foundations of micromechanics and microelectronics. Owing to this, it has become possible to create compact integrated multielement and multifunctional systems of miniature EMECs, combined in a single integrated circuit [8]. When solving a set of primary tasks, this allows one to achieve a new quality level in mass-and-size parameters, speed, functionality, productivity, cost reduction, etc.

In this case, dynamic processes of energy generation in various devices, circuits, and subsystems are of electromechanical nature, whereas the structural functional elements can be a part of or a finalized MEMS device with size 0.1 μm < l < 0.1 mm (at least in one direction) [9–11].

Currently, a qualitatively new level of development of modern electromechanics predetermines the introduction of the latest achievements of nanoscience and nanotechnology in those branches of natural sciences, engineering sciences, and technology that are of fundamental importance for electromechanics and industry as a whole.

The primary task of modern electrical engineering is the development of electrical materials science in the entire energy spectrum. Active research of practical applications of electrical materials with various purposes manufactured by nanotechnology are currently underway.

Among nanomaterials promising for electrical engineering, one can allocate amorphous alloys, graphene, magnetic ferro-paper, carbon nanotubes, metal powders in electrically conductive layers, new friction and electrically insulating materials, etc. Specific magnetic losses of magnetic circuits from amorphous and nanocrystalline alloys are significantly less than those for electrical steel and ferrites (less than 0.1 W/kg at f = 60 Hz). They have a high relative initial magnetic permeability, as well as saturation induction at industrial and high frequencies (B_S = 1.2–1.3 T). For example, graphene is the newest nanostructured material with unique conductive properties, which allow it to be both a very good conductor and semiconductor. In addition, graphene is extremely durable and can withstand huge rupture and flexure loads.

Another example of nanotechnology application is the manufacturing of magnet wire using a fine silica powder chemically introduced into polyamide insulation. This method enables increasing the finished wires quality and its temperature index to 280°C.

From the above we can conclude that the introduction of nanostructured electrical materials in EMEC production in macrosystem electromechanics can contribute to an integrated increase in the level of modern electrical engineering (especially large-scale). However, this process is still limited by technical and technological difficulties of manufacturing and the high cost of these materials [12–14].

The term “nanosystem electromechanics” should be used when nanotechnologies and nanomaterials are applied in microsystem electromechanics.

This relates to cases where the sizes and power of the EMECs are comparable with the power of biological energy converters. In these cases, minimum-size man-made devices are comparable with the largest molecules of living organisms. At such power level, nanoelectromechanics is the dominant strategic direction of modern nanoscience, in which electromechanical systems (NEMS) having structural functional elements with a size of 10 nm < l < 100 nm are studied (at least in one direction) [15, 16].

The solution of the primary tasks of modern microsystem electromechanics requires further in-depth study of the structure of matter, the synthesis of processes in matter, finding methods for producing crystalline lattices of conductors, dielectrics, semiconductors, diamagnetics, and ferromagnetics with a regular distribution of atoms and molecules, depending on the properties and destination of the materials, as well as creating conductors and semiconductors based on polymers and other chemical compounds. A drastic improvement in the quality of atomic and molecular compounds, and composite materials in devices that directly convert thermal, solar, atomic, and chemical energy into electrical energy with high efficiency is required. From this point of view, contemporary nanostructure materials science is the most promising.

In [17, 18], we carried out a comparative analysis and classification of dynamic and structural characteristics of the basic functional elements of MEMS and NEMS by their operation principles. This analysis was performed from the point of view of micro- and nanominiature interpretations of the basic principles and theoretical ideas of modern electrophysics.

It was found that, despite similar characteristics between MEMS and NEMS, within functional principles of MST, there is fundamental differences in the key features of the dynamic and energy state of these systems.

We can briefly summarize the main features of MEMS and NEMS as follows.

• Nanosystem technology uses the limit opportunities for superminiaturization of electrical, magnetic, mechanical, and biological systems.

• In the production of MEMS, the process of miniaturization of functional elements obeys common regularities of development of modern microsystem technology. It can be performed using “top down” technologies and models (descending-type production). These models implicitly suggest that reducing the size of structures does not affect their functional properties (and the principle of operation). In contrast, in the production of nanosystems (including NEMS), “bottom-up” technologies (ascending-type production), which are based on atomic and molecular synthesis (the so-called “molecular assembly” or “atomic assembly”), are of paramount importance.

• Since dynamic processes of electromagnetic field transformation in MEMS are due to gravity (inertness) of micromechanical elements, their physical and mathematical modeling can be performed using the classical Faraday–Maxwell laws of electrophysics (and, accordingly, the classical theory of electrical circuits).

• Since in nanosystem technology (and, respectively, in NEMS), gravity forces are insignificant compared to the interatomic and intermolecular forces of chemical bonds, the laws of classical electrophysics in the problems of physical and mathematical NEMS modeling (and the corresponding theory of electrical circuits) must be corrected in accordance with quantum electrophysics laws.

• Products of microsystem technology in the field of MEMS are purely technical in their structure. In contrast, in the field of nanosystem technology, fundamental research is needed when creating NEMS products in which the acting technical and natural functional elements are harmoniously combined.

• Currently, based on natural analogs (for example, using the capabilities and functional properties of biological nanostructures), work is underway to create NEMS in which elements of living organisms (biomolecules, bacteria, etc.) perform part of the functions. Since man-made NEMS can operate in a wide range of temperatures (from low temperatures up to several hundred degrees) and in various aggressive environments, it’s natural that the technological motive is now one of the main motives that encourage us to study living matter at the nanoscale. It can be argued that the current development of nanosystem electromechanics predetermines the path to the creation of nature-like technology [19, 20].

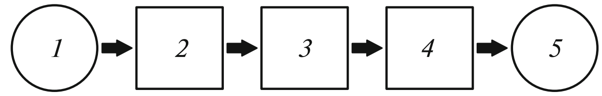

Fig. 2. General structure of NEMS: input signal (*1*), sensor (*2*), control and signal processing circuit (*3*), nanoactuator (*4*), and output signal (*5*).

The following discoveries of the past 20 years contributed to NEMS development:

• creating carbon nanotubes and applying probe microscopes and lithographic methods for assembling resultant tubes into separate devices;

• possibility of placing individual molecules in the gap between the electrodes and measuring the charge transfer through these molecules;

• development of probe methods for manipulating individual atoms of matter and creating nanostructures;

• development of methods of chemical synthesis of nanocrystals and methods for combining them into larger ordered structures;

• allocation of biochemical “molecular engines” and their inclusion into a non-biological environment [21, 22].

The elemental base of NEMS and nanorobotics are carbon nanotubes (possessing exceptional physical and electrical properties), carbon frame structures (for example, fullerene C_{60}), molecular motors, molecular switches, DNA complexes, etc., or their subsystems, which can be part of or a complete NEMS product. The general structure of NEMS includes sensory elements (information sensors or nanosensors), energy and information transfer channels, control devices, and actuators (for example, nanoactuators) (Fig. 2) [15].

ISSUES OF GENERALIZED PHYSICOMATHEMATICAL SIMULATION AND AUTOMATED MEMS AND NEMS DESIGN

At the turn of the 20th and 21st centuries, progress in development of theories and models of EMECs and their systems (especially for microsystems) was mainly related to the use of more powerful computer programs, and to a much lesser extent due to the emergence of new theoretical concepts and models [23].

For further development of microsystem electromechanics (especially at the nanostructural level), the improvement of theoretical methods and models, in-depth study of electromagnetic and thermal fields, and refinement of numerical methods for studying transient electrophysical processes in the tasks of computer-aided MEMS and NEMS design is especially important.

In this paper we propose a new approach for solving some key issues of generalized physical and mathematical modeling, allowing consideration of a large number of interrelated factors, which determine the basic dynamic and energetic characteristics of MEMS and NEMS.

Based on the main theoretical and technological principles of modern electromechanical science and microelectronics, a clear physical and mathematical interpretation of MEMS and NEMS terms and their classification according to dynamic and functional characteristics is of paramount importance.

ON THE PHYSICAL PRINCIPLES OF THEORETICAL ELECTROMECHANICS

In most modern studies in the field of theoretical foundations of electrical engineering, especially in complex problems of simulating the processes of generation, transmission, and consumption of electrical energy, basic principles are the concepts of binary-conjugate electrophysics. In this case, the processes of electromagnetic field transformations depend on topological characteristics of functional structures [24], namely:

• in the entire range of the energy spectrum, analysis and synthesis of electrical systems with a working (dynamic) magnetic field, including electro-inductive (induction) EMECs, is carried out on the basis of the generalized Lagrange–Maxwell energy state space and, correspondingly, using Faraday–Maxwell equations of electromagnetic field transformation;

• in the entire range of the energy spectrum, analysis and synthesis of electrical systems with a working (dynamic) electric field, including magneto-inductive (capacitive) EMECs, is carried out on the basis of the generalized space of energy state and, correspondingly, by using the modified system of Faraday–Maxwell equations.

Applying the above modeling approach to electromechanical systems allows us to give the following generalized definition of the MEMS and NEMS terms.

Definition 1: MEMS is a multi-element dynamic system (set) of non-linearly interacting binary-conjugate (electro-induction and magnetic-induction) microminiature electromechanical energy conversions (microminiature EMECs).

Definition 2: NEMS is a multi-element dynamic system of non-linearly interacting binary-conjugate (electro-induction and magneto-induction) nano-electromechanical energy conversions (nano-EMECs).

With the above interpretation of MEMS, their generalized physical and mathematical modeling can be carried out based on the study of dynamic modes and energy characteristics of microminiature EMECs, based on the integral principle of electromechanics [25–27], which is expressed in the following binary-conjugate equivalent forms.

• For electro-induction (inductive) microminiature EMEC:

$$E_B(t)dt = \sum_1^n d\left(\oint m_i V_i dl_i + \iint d\Psi_i dq_i\right), \qquad (1)$$

where n is the number of current loops, m_i is the mass, V_i is the velocity, q_i is the electric charge, and Ψ_i is the magnetic flux coupling of the ith loop of current.

• For magneto-inductive (capacitive) microminiature EMEC:

$$E_B^*(t)dt = \sum_1 d\left(\oint m_j^* V_j^* dl_j + \iint dQ_j^* d\psi_j^*\right), \qquad (2)$$

where h is the number of voltage contours, m_j^* is the mass, V_j^* is the velocity, Q_j^* is the operational electric flux coupling, and ψ^* is the magnetic flux induced by the working electric field for the jth voltage contour.

In Eqs. (1) and (2), energy functions $E_B(t)$ and $E_B^*(t)$ characterize the intensity of EMEC interaction with the external environment. In isolated electromechanical bodies, $E_B = E_B^* = 0$.

For convenience of theoretical analysis of dynamic phenomena, especially in complex coupled electromagnetic contours, it is expedient to represent energy state factors $\Psi(r, t)$, $q(r, t)$ and $Q^*(r, t)$, $\psi^*(r, t)$ conventionally in the form of axial generalized vectors:

$$\Psi = |\Psi| e_\Psi; \quad Q^* = |Q^*| e_{Q^*}, \\ q = |q| e_q; \quad \psi^* = |\psi^*| e_\psi, \qquad (3)$$

where e_Ψ, e_q, e_{Q^*}, and e_{ψ^*} are the unit vectors characterizing the spatial orientation of the corresponding axes of the flux linkage.

In the general case, for complex interrelated microminiature EMEC loops, it is expedient to represent energy state factors $\Psi(r, t)$ and $Q^*(r, t)$ in (1) and (2) as functionals of matrices of current-vectors and voltage-vectors $I(r, t) = \dot{q}(r, t)$ and $V^*(r, t) = \dot{\psi}^*(r, t)$ using the following expansions:

$$\Psi(\dot{q}(r,t)) = \frac{d\Psi}{d\dot{q}}\dot{q} + \frac{d^2\Psi}{d^2\dot{q}}\dot{q}^2 + \ldots, \\ Q^*(\dot{\psi}^*(r,t)) = \frac{dQ^*}{d\dot{\psi}^*}\dot{\psi}^* + \frac{d^2Q^*}{d^2\dot{\psi}^*}\dot{\psi}^{*2} + \ldots. \qquad (4)$$

From (4) in the first approximation we have

$$\Psi(\dot{q}(r,t)) = \frac{d\Psi}{d\dot{q}}\dot{q} + \ldots = \widehat{L_D} I + \ldots, \\ Q^*(\psi^*(r,t)) + \frac{dQ^*}{d\dot{\psi}^*}\dot{\psi}^* + \ldots = \widehat{C_D} V^* + \ldots, \qquad (5)$$

where $\hat{L}_{\mathrm{D}} = \dfrac{d\Psi}{d\dot{q}}$ and $\hat{C}_{\mathrm{D}} = \dfrac{dQ^*}{d\psi^*}$ are the matrices of dynamic inductance and capacitance of microminiature EMECs.

From these expressions, one can get the initial equations of electrodynamics and electromechanics of microminiature EMECs in vector-matrix forms.

• For induction EMEC we have

$$\begin{gathered} \frac{d\Psi}{dt} + \widehat{R_{\mathrm{D}}}J = V_L, \\ F_{\mathrm{EM}} = -\frac{d}{dx}W_L = -\frac{d}{dx}\left[I^{\mathrm{T}}\frac{d\hat{L}_{\mathrm{D}}}{dx}I\right], \\ W_L = I^{\mathrm{T}}\frac{d\hat{L}_{\mathrm{D}}}{dx}I, \end{gathered} \tag{6}$$

where W_L is the working magnetic field energy, V_L is the voltage of generation of external energy sources, I the matrix of conduction currents, I^{T} is the transposed matrix of currents, $\hat{R}_{\mathrm{D}} = \dfrac{d\Psi}{dq}$ is the matrix of dynamic internal resistances, and F_{EM} is the electromechanical force acting on moving parts of microminiature EMEC.

• For capacitive EMEC we have

$$\begin{gathered} \frac{dQ^*}{dt} + \hat{G}_{\mathrm{D}}V^* = I_C^*, \\ F_{\mathrm{EM}}^* = -\frac{d}{dx^*}W_C = -\frac{d}{dx^*}\left[V^{*\mathrm{T}}\frac{d\hat{C}_{\mathrm{D}}}{dx^*}V^*\right], \\ W_C = V^{*\mathrm{T}}\frac{d\hat{C}_{\mathrm{D}}}{dx^*}V^*, \end{gathered} \tag{7}$$

where W_C is the working electric field energy, I_C^* are the generated currents fed to external circuit, $V^{*\mathrm{T}}$ is the transposed matrix of voltages, $\hat{G}_{\mathrm{D}} = \dfrac{dQ^*}{d\psi^*}$ is the matrix of dynamic internal conductance, and F_{EM}^* is the electromechanical force acting on moving parts of microminiature EMEC.

Without loss of generality, one can assume that MEMS corresponding to Definition 1 (as a complex system) consists of M nonlinearly coupled electroinduction EMECs and N magneto-induction EMECs (Fig. 3).

Therefore, the dynamic behavior of MEMS can be described on the basis of modifications of the main theoretical propositions of the principle of least action for dissipative systems in a certain $\langle M + N\rangle$- dimensional space of axial generalized vectors (mechanical and electrophysical energy state factors of microminiature EMECs), namely $(\alpha, \beta) = (x^{\mathrm{o}}, P^{\mathrm{o}}; q^{\mathrm{o}}, \Psi^{\mathrm{o}}; \psi^{*\mathrm{o}}, Q^{*\mathrm{o}})$ [25, 26]. In this case, we use the following definitions:

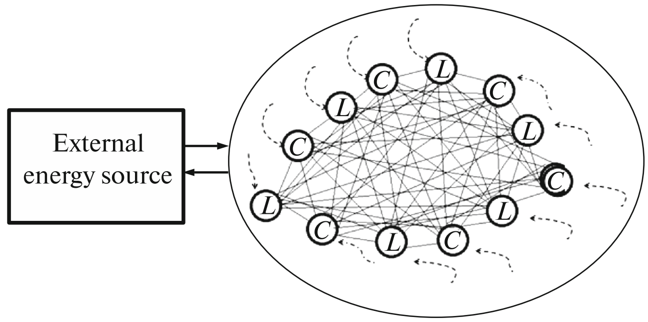

Fig. 3. General schematic MEMS representation: electro-induction (inductive) microminiature EMECs (L), magnetic-induction (capacitive) microminiature EMECs (C).

α is the subvector of generalized mechanical and physical coordinates of MEMS

$$\left.\begin{aligned} &\alpha = (x^o, q^o, \psi^{*o}) \\ &x^o = (x_L, x_C) \\ &x_L = (x_1, x_2, \dots, x_M), \\ &x_C = (x_1^*, x_2, \dots, x_N^*), \\ &q^o = (q_1, q_2, \dots, q_M) \\ &\psi^{*o} = (\psi_1^*, \psi_2^*, \dots, \psi_N^*) \end{aligned}\right\} \tag{8}$$

β is the subvector of generalized mechanical and electrophysical momenta of MEMS

$$\left.\begin{aligned} &\beta = (P^o, \Psi^o, Q^{*o}) \\ &P^o = (P_L, P_C) \\ &P_L = (P_1, P_2, \dots, P_M), \\ &P_C = (P_1^*, P_2^*, \dots, P_N^*), \\ &\Psi^o(\Psi_1, \Psi_2, \dots, \Psi_M) \\ &Q^{*o} = (Q_1^* Q_2^*, \dots, Q_N^*). \end{aligned}\right\} \tag{9}$$

According to the generalized formulation of the principle of least action for dissipative systems, the simulation of dynamic modes in MEMS can be carried out in the generalized space of energy state, (α, β), which is characterized by the specific function of energy state; the Lagrange function $\mathcal{L}(\alpha, \dot{\alpha}, t)$ for a given MEMS. In this state, the behavior of the system between the fixed positions *1* (at $t = t_1$; $\alpha_1 = (x_1^o, q_1^o, \psi_1^o)$) and *2* (at $t = t_2$; $\alpha_2 = (x_2^o, q_2^o, \psi_2^{*o})$) (Fig. 4) obeys the full action extremum principle

$$\begin{gathered} \mathcal{S} = \int_{t_1}^{t_2} \mathcal{L}(\alpha, \dot{\alpha}, t)dt, \\ \alpha(t) = \arg\min_{\alpha(t)} \mathcal{S}, \\ \delta\mathcal{S} = 0. \end{gathered} \tag{10}$$

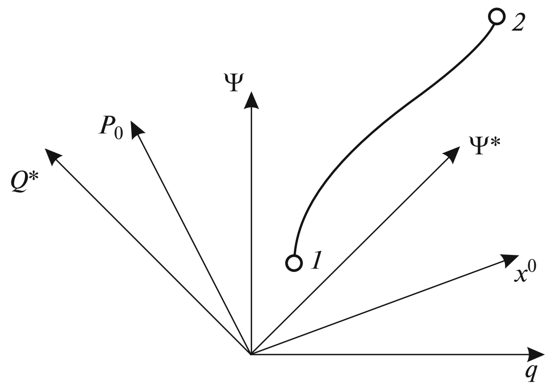

Fig. 4. MEMS dynamic mode trajectory in multidimensional space of energy states.

Here, action $\mathcal{S}$ is defined as a functional of Lagrangian $\mathcal{L}(\alpha, \dot{\alpha}, t)$, expressed in the form of the difference between effective electrokinetic $T(\dot{\alpha}(t))$ and effective electropotential $U(\alpha(t))$ energies on the dynamic trajectory of MEMS in multidimensional space (α, β).

From (4)–(10) we obtain the generalized Lagrange equation of the second kind, expressed in the vector-matrix form:

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\alpha}}\right) - \left(\frac{\partial \mathcal{L}}{\partial \alpha} + \frac{\partial \Phi}{\partial \dot{\alpha}}\right) = F^0. \quad (11)$$

In (11), $\dot{\alpha}(t)$ and $F^0(t)$ are the subvectors of mechanical and electrophysical generalized velocities and forces of functional elements of MEMS

$$\dot{\alpha}(t) = \left(I^0 = \frac{dq^0}{dt}; V^{*0} = \frac{d\psi^{*0}}{dt}; \mathcal{V}^0_L = \frac{dx_L}{dt}, \mathcal{V}^0_C = \frac{dx_C}{dt}\right),$$
$$F^0(t) = \left(E = -\frac{d\Psi^0}{dt}; M^* = -\frac{dQ^0}{dt}, F_M = \frac{dP^0}{dt}\right). \quad (12)$$

Here, E is the generalized vector of electromotive forces (EMFs) acting on inductive elements of MEMS, M^* is the generalized vector of magnetomotive forces (MMFs) acting on magnetically conductive MEMS structures, and F_M is the generalized vector ((⟨M + N⟩)-dimensional) of mechanical forces, acting on movable elements of MEMS.

In (11), the generalized dissipative Rayleigh function consists of mechanical and electrophysical terms, $\Phi_M(\mathcal{V}^0_L; \mathcal{V}^0_C)$ and $\Phi_E(I^0; V^{*0})$, respectively

$$\Phi(\dot{\alpha}) = \Phi_M(\mathcal{V}_L) + \Phi_E(I_i, V^*_j). \quad (13)$$

Considering approximations (4) and (5) for $\Phi_E(I^0; V^{*0})$, we obtain expression

$$\Phi_E(I^0; V^{*0}) = -\frac{1}{2}(I^0 \hat{R}_D I^{0t} + V^{*0} G_D V^{*0t}). \quad (14)$$

For the generalized MEMS model, the Lagrangian can be constructed by introducing the $(M \times N)$-dimensional interaction tensor (tensor of mutual influence) between magnetic (electro-induction) and capacitive (magneto-induction) functional MEMS elements, $(\widehat{K^M_N})$ (q^0, ψ^{*0}). It takes explicit form

$$\widehat{K^M_N}(q^0, \psi^{*0}) = \begin{bmatrix} K^N_M(q_1, \psi^{*1}) & \dots & K^N_M(q_1, \psi^{*N}) \\ \vdots & & \vdots \\ K^N_M(q_M, \psi^{*1}) & \dots & K^N_M(q_M, \psi^{*N}) \end{bmatrix}. \quad (15)$$

In this case, the generalized Lagrange function for MEMS can be written as

$$\mathcal{L} = \mathcal{L}_L + \mathcal{L}_C + \Delta\mathcal{L}_{LC}, \quad (16)$$

where $\Delta\mathcal{L}_{LC}$ is the Lagrangian component that considers the nonlinear electrophysical interaction between functional elements of the system corresponding to electric induction (inductive) and magnetic induction (capacitive).

In the general case, for the combined study of dynamic processes in MEMS, the Lagrangian terms in (16) have form

$$\mathcal{L}_L = (x_L, q^0, \dot{x}_L, \dot{q}^0, t) = T_L(\dot{x}_L, \dot{q}^0, t) - U_L(x_L, q^0),$$
$$\mathcal{L}_C = (x_C, \psi^{*0}, x_C, \dot{\psi}^{*0}, t) = T_C(x_C, \dot{\psi}^{*0}, t) U_C(x_C, q^0),$$
$$\Delta\mathcal{L}_{LC} = \dot{q}^0 \widehat{K^M_N}(q^0, \psi^{*0})\dot{\psi}^*)\dot{\psi}^{*0t}. \quad (17)$$

Moreover, T_L, T_C, U_L, and U_C are given by

$$T_L = T^M_L + T^E_L, \quad T_C = T^M_C + T^E_C \quad (18)$$

and

$$U_L = U^M_L + U^E_L, \quad U_C = U^M_C + U^E_C, \quad (19)$$

where T^M_L and T^M_C are the energies of mechanical motion of movable functional MEMS elements

$$T^M_L = \frac{1}{2}\sum_{i=1}^{M} m_i x_i^2, \quad T^M_C = \frac{1}{2}\sum_{i=1}^{N} m^*_j \dot{x}^{*2}_j. \quad (20)$$

Moreover, T^E_L and T^E_C are the corresponding electrokinetic energies

$$T^E_L = \left(\sum_{l=1}^{M}\sum_{j=1}^{M} \dot{q}_l \widehat{L_{lj}} \dot{q}^t_j\right) = q^0 \hat{L}^0,$$
$$T^E_C = \left(\sum_{l=1}^{N}\sum_{j=1}^{N} \dot{\psi}^*_i \widehat{C_{lj}} \dot{\psi}^{*t}_j\right) = \psi^{0*}\widehat{C^0}\psi^{0*t}. \quad (21)$$

In (21), $\widehat{L^0} = \widehat{L_{lj}}$ is the matrix of self and mutual inductances, and $\widehat{C^0} = \widehat{C_{lj}}$ is the matrix of self and mutual capacitances of functional MEMS elements, U_L^M and U_C^M are the accumulated mechanical energies, and U_L^E and U_C^E are the corresponding electrophysical potential energies accumulated in the inductive (L_{Hi}, $i = 1, ..., M$) and capacitive ($C_{Hj}, j = 1, ..., M$) static elements of MEMS

$$U_L^{ec} = \frac{1}{2}\sum_{i=1}^{N} \dot{q}_l \widehat{L_{HL}} \dot{q}_l^{\mathrm{t}}, \quad U_C^{ec} = \frac{1}{2}\sum_{j=1}^{F} \dot{\psi}_j^* \widehat{C_{Hj}} \dot{\psi}_j^{*\mathrm{t}}. \tag{22}$$

The joint solution of system of equations (11) and (16)–(19) completely determines the dynamic behavior of generalized MEMS in any modes of interaction of functional elements. In this case, dynamic equations of MEMS take the vector-matrix form, namely:

• Electrodynamics equations

$$\frac{d}{dt}\Psi^0 + \dot{q}^0\widehat{R_\mathrm{D}} + \dot{\psi}^{*0}\frac{d\widehat{K_N^M}}{dt}\dot{\psi}^{*0t} + \widehat{K_N^M}\frac{d^2\psi^{*0}}{dt^2} = \dot{\psi}_{CL}^{*0}, \quad \frac{dQ^0}{dt} + \psi^{*0}\widehat{C_\mathrm{D}} + \dot{q}^0\frac{d\widehat{K_N^M}}{dt}\dot{q}^{0\mathrm{t}} + \widehat{K_N^M}\frac{d^2q^0}{dt^2} = \dot{q}_{LC}^0. \tag{23}$$

• Equations of electromechanical forces acting on functional MEMS elements

$$F_E^0 = \frac{d}{dx^0}[(\dot{q}^0\hat{L}^0\dot{q}^{0\mathrm{t}}) + (\dot{\psi}^{*0}\widehat{C^0\dot{\psi}^{*0\mathrm{t}}}) + (\dot{q}^0\widehat{K_N^M}\dot{\psi}^{0\mathrm{t}})], \tag{24}$$

where $\dot{q}_{LC}^0$ and $\dot{\psi}_{CL}^{*0}$ are the subvectors of currents and voltages between capacitive and inductive functional MEMS elements

$$\dot{q}_{LC}^0 = (\dot{q}_{LC/1}, \dot{q}_{LC/2}, \ldots, \dot{q}_{LC/M}), \quad \dot{\psi}_{CL}^{*0} = (\dot{\psi}_{CL/1}^*, \dot{\psi}_{CL/2}^*, \ldots, \dot{\psi}_{CL/N}^*). \tag{25}$$

Systems of equations (23) and (24) have a universal character for MEMS with all types of design, and their joint solution entirely determines the dynamic behavior of the generalized MEMS model in any mode of operation.

For studying MEMS with a specific design in computer-aided design problems, all structural features of functional elements in these equations should be accounted for.

It should be noted that the main analytical properties of elements of interaction tensor $\widehat{K_N^M}(q^0, \psi^{*0})$ are the following: tensor elements $\widehat{K_N^M}(q^0, \psi^{*0})$ are continuous functions, have continuous derivative $\frac{d}{dt}K_N^M(q_i, \psi^{*j})$, and satisfy conditions

$$\left.\begin{aligned} &\lim_{q_i\to 0} K_N^M(q_i, \psi^{*j}) = \lim_{\psi_j\to 0} K_N^M(q_i, \psi^{*j}) = 0, \\ &0 \le |K_N^M(q_i, \psi^{*j})| \le k_1, \\ &\int_0^{q_{\max}}\int_0^{\psi^*_{\max}} K_N^M(q_i, \psi^{*j})dq_i d\psi^{*j} \le k_2, \end{aligned}\right\} \tag{26}$$

where k_1 and k_2 are positive values.

In this case, dependences of the interaction tensor components on MEMS design parameters can be determined using experiment planning theory [27, 28], representing them in the form of a quadratic decomposition:

$$K_N^M(q_i, \psi^{*j}) = K_N^M(q_i, \psi^{*j}) + \sum_{i=1}^{M}\beta_i q_i + \sum_{j=1}^{N}\mu_i\psi^{*j} + \sum_{i=1}^{M}\sum_{j=1}^{N}\gamma_{ij}q_i\psi^{*j} + \ldots, \quad i = 1, 2, \ldots, M; \quad j = 1, 2, \ldots, N, \tag{27}$$

where β_i, μ_j, and γ_{ij} are the coefficients of a quadratic form, which are determined by design features of functional MEMS elements.

Physical and technical reasoning for the use of basic principles and propositions of binary-conjugate electrophysics in problems of studying dynamic characteristics of EMECs and their systems was performed in [4, 5, 17], where the following key issues were addressed:

• Electrophysical simulation of the energy conversion processes between functional elements of nano-EMECs.

• Interaction of nano-EMECs with the external environment.

• Consideration of nano-EMECs in a system of other nanostructures.

• Complex physical, mathematical, and computer simulation of NEMS as a result of these studies.

For generalized physical and mathematical simulation and computer-aided design of EMECs, original basic equations of electric-induction and magnetic-induction electromechanics (equations of electromagnetic field conversion in the subareas of inductance *L* and capacitance *C* of the *LC*-contour, respectively) must be adjusted according to the fundamental principles of quantum electrophysics. One should consider the following key factors.

1. For electric-induction nano-EMECs an elementary functional element of energy transformation (the base cell) is a closed superconducting nanotube. Its energy state in the phase space of generalized Lagrange–Maxwell forces ($\psi(t)$, $q(t)$) is represented as a fixed point of stability.

2. For magnetic-induction EMECs, an elementary functional element of energy conversion (base cell) is

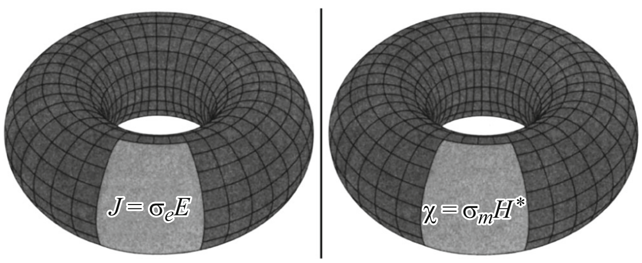

Fig. 5. Schematics of closed electrically conductive (a) and magnetically conductive (b) nanotubes.

a closed super-magnetically conductive nanotube. Its energy state in the conjugated phase space ($Q^*(t)$, $\psi^*(t)$) is represented as a fixed point of stability (Fig. 5).

Nanoactuators in biophysics are an example of what has been said. For example, when considering the positions that protein and nucleic acid molecules can occupy, we face similar topological characteristics of living structures. For the energy exchange of a molecule with an external environment, it is necessary to break the chemical bonds of this section of the polymer chain. The consumption of energy in such a process is quite significant, therefore, at a sufficiently low temperature and weak effects of external electromagnetic fields, the probability of molecule destruction is small, and the molecule can exist long enough in the state of minimum energy [28].

Closed conductive and magnetic conductive nanotubes in the electric-induction and magnetic-induction subareas of energy transformation can form binary-connected (interconnecting) regions around themselves. With weak disturbances caused by external mechanical loads, the energy states of electromagnetic and thermal fields (not violating the topology of nanostructure and its superconducting state) remain unchanged.

The energy exchange of nanotubes with the external environment requires separating the binary-connected regions into singly-connected ones or considering the effect of electromagnetic and thermal fields disrupting the superconducting state of nanotubes.

In this case, in the problems of physical and mathematical analysis of energy conversion in nano-EMECs, conductive and magnetically-conductive open-ended nanotubes can be considered as a quantum-mechanical analog of the electromagnetic oscillatory LCR-circuit. Geometric parameters of this contour cannot be accurately measured. They are characterized by the principles of quantum electrophysics [29–31].

A more specific application of developed theoretical principles of modeling of microminiature EMECs (and MEMS) for physical and mathematical (and corresponding computer) simulation of nano-EMECs (and NEMS) is the problem of special research projects.

CONCLUSIONS

The study addresses some key issues of electrophysical simulation of MEMS and NEMS. A new generalized research approach is proposed to study the dynamic and energy characteristics of MEMS and NEMS as complex dynamic systems with binary-conjugate subsystems.

Systems of equations are obtained, which completely describe dynamic and energetic behavior of generalized MEMS and NEMS models in any operation mode.

Based on the proposed theoretical principles and models, we discuss the opportunities in studying electrophysical characteristics of biological nanostructures.

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