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PHYSICAL FIELDS OF DYNAMICALLY CONTROLLED HYDROACOUSTIC RADIATOR WITH RADIAL POLARIZATION

The nature of the polarization of piezoceramic elements plays an important role in the construction of piezoceramic hydroacoustic transducers with dynamically controlled parameters from the electrical side. However, to quantify this role, depending on the polarization, radial or circumferential, of the transducer's piezoelectric elements, appropriate calculation ratios are required. By the method of coupled fields in multiconnected domains taking into account the connectivity of electric, mechanical and acoustic fields during energy conversion and acoustic interaction of transducer elements during its formation, expressions for the named physical fields depending on amplitudes and phases are calculated.

Keywords: *piezoceramic transducer, radial polarization, dynamic electric excitation.*

INTRODUCTION

The tendency to reduce the operating frequencies of hydroacoustic stations (HAS), while maintaining their directional properties, their versatility and lack of opportunities to increase the size of ship compartments, which house hydroacoustic antennas of HAS, forces to search for ways to dynamically control the parameters of hydroacoustic antennas [1–5]. Since hydroacoustic transducers are electromechanical oscillating systems [6], formed from two interconnected parts in a single structure – electrical and mechanical, then, of course, for the technical implementation of the task of dynamic control of transducers it is necessary to use the electrical part [7, 8]. But for this purpose it is necessary to change in some way the scheme of construction of the hydroacoustic transducer, having entered into its design structure: first, elements by means of which it is possible to carry out electric control of its parameters; and, secondly, the elements by which it is possible to provide a physical connection between all the elements of the transducer. Regarding the cylindrical hydroacoustic transducer, such a scheme of its construction is proposed in [7, 8]. According to it, the transducer is formed of two piezoceramic shells with parallel longitudinal axes placed in each other so that the longitudinal axes of the shells are either coaxial or spaced inside. The space between the shells is filled with some elastic medium. It can be gaseous or liquid. Introduction to the transducer of the second shell allows to electrically control the properties of the transducer, changing the amplitude and phase of the electrical signals of the excitation of the shells. Filling the space between the shells with an elastic medium creates the conditions for their physical interaction with each other through the acoustic field formed in this space due to the sound waves emitted and repeatedly reflected by each of the shells.

This proposed construction of the hydroacoustic transducer has many control factors for its parameters. It is known [6, 9] that the hydroacoustic transducer performs two interrelated functions – the conversion, in particular, of electrical energy into mechanical and acoustic and the formation of acoustic energy in the surrounding elastic media. For piezoceramic transducers, the control factors for their energy conversion parameters are:

amplitudes and phases of excitation voltages;

composition and polarization of piezoceramics;

physical characteristics of elastic media in the internal spaces of the transducers;

geometric characteristics of transducer designs.

In the formation of acoustic energy to these factors a wave dependence associated with the frequency of the transducer is added.

Analytical determination of physical fields that are formed during the operation of dynamically controlled transducers of this type of construction is associated with the following interactions:

interaction of electric, mechanical and acoustic fields during energy conversion;

acoustic interaction of structural elements of transducers due to radiation and repeated reflection of sound wave shells;

interactions in transducers of processes of transformation and formation of energy.

The fundamental point of consideration of all these interactions is the choice of the nature of the polarization of the piezoceramic elements of the transducers. This is due to the type of differential equations that describe the behavior of piezoceramic shells in the computational models of the studied transducers. The literature describes the physical fields of electrically dynamically controlled transducers of the cylindrical type when used in the construction of their circumferential polarization [10].

The aim of this work is to determine the analytical relations that arise in a dynamically controlled cylindrical hydroacoustic transducer with radial polarization of its piezoceramics. A technical example of such a transducer is shown in Fig. 1.

Fig. 1. Sample ring transducer

FORMULATION OF THE PROBLEM

The physical model of the dynamically excited hydroacoustic transducer (Fig. 2) is two cylindrical piezoceramic shells – outer 1 and inner 2 with parallel longitudinal axes. The axes are spaced apart in $l_{O_2O_1}$. The space between the shells 1 and 2 is filled with an elastic medium. The inner shell 2 is evacuated or also filled with an elastic medium. Both shells are solid and their cylindrical surfaces are covered with thin electrodes. Exciting electrical voltage signals are supplied to the electrodes for the outer 1 shell $\psi_1 = \psi_{i_1} e^{-i\omega t}$ and for the inner 2 shell $\psi_2 = \psi_{i_2} e^{-i(\omega t + a)}$. Here ψ_1 and ψ_2 – the amplitudes of the excitations, and a – the phase shift between them. The shells have respectively average radii r_1 and r_2 and thicknesses h_1 and h_2 are small relative to their radii. The transducer is placed in an infinitely elastic medium.

According to the described physical model, the calculation model (Fig. 2) is as follows.

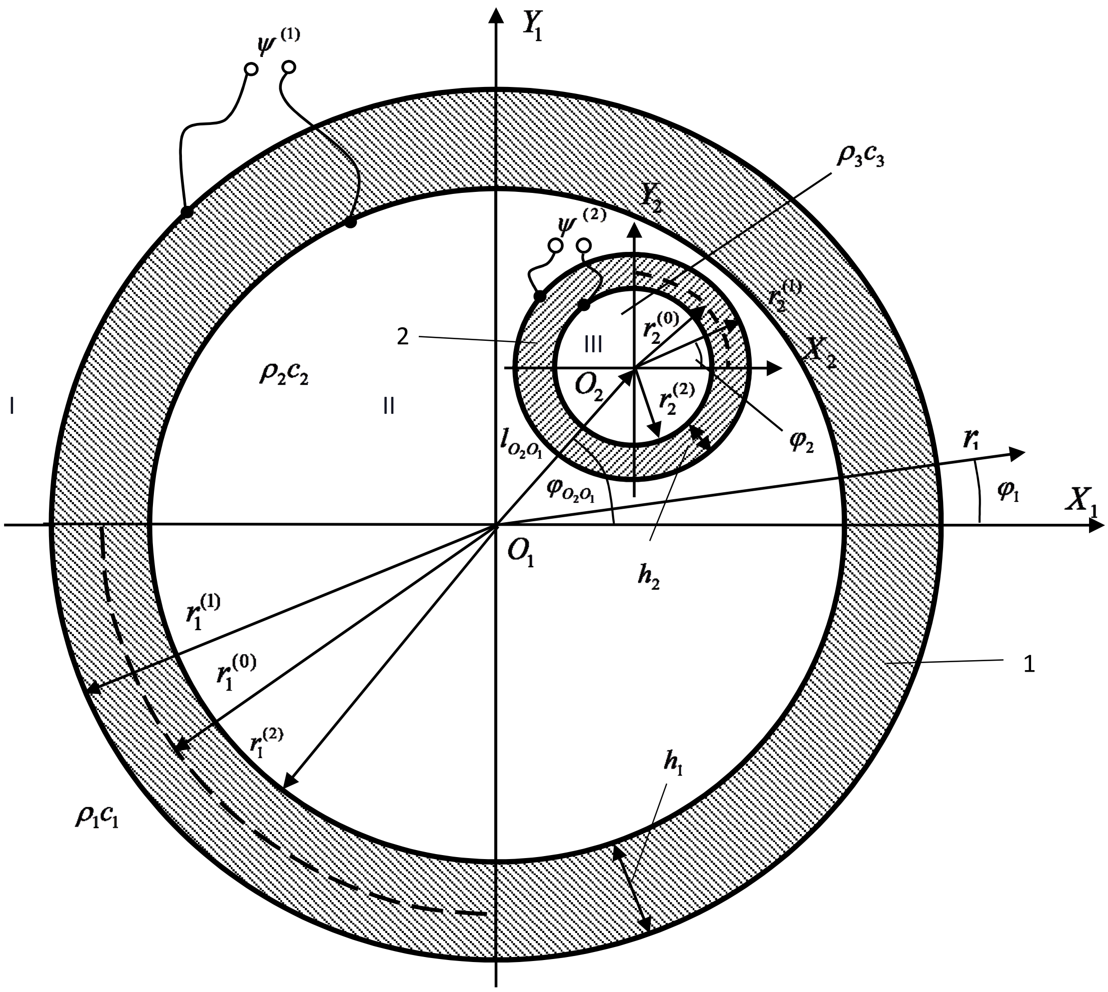

Fig. 2. Normal cross section of a cylindrical hydroacoustic transducer

We introduce local Cartesian and circular cylindrical coordinates associated with each of the shells: $O_1X_1Y_1Z_1$ and $r_1\varphi_1z_1$ – for the outer (s = 1) shell and $O_2X_2Y_2Z_2$ and $r_2\varphi_2z_2$ – for the inner (s = 2) shell. The space of existence of the sound field of the transducer is divided into 3 partial areas (j = 1, 2, 3): outer (j = 1), inner between the shells (j = 2) and inner of the second shell (j = 3).

The above physical features of the processes of transformation and energy formation by a dynamically excited transducer, associated with the interaction of fields and these processes, mathematically in the calculation model are reflected in the joint solution of the system of differential equations, which includes:

– Helmholtz equation, which describes the oscillating motion of the media inside and outside the transducers of the system:

$$\Delta\Phi_j^{(s)} + k_j\Phi_j^{(s)} = 0,\ j = 1, 2, 3; \qquad (1)$$

– equations of motion of thin piezoceramic shells with radial polarization in displacements:

$$\left(1+\beta_S\right)\frac{\partial^2 u^{(S)}}{\partial\varphi_S{}^2} + \frac{\partial w^{(S)}}{\partial\varphi_S} - \beta_S\frac{\partial^3 w^{(S)}}{\partial\varphi_S^3} = a_S\gamma_S\frac{\partial^2 u^{(S)}}{\partial t^2}, \qquad (2)$$

$$-\frac{\partial u^{(S)}}{\partial\varphi_S} + \beta_S\left(\frac{\partial^3 u^{(S)}}{\partial\varphi_S^3} - \frac{\partial^4 w^{(S)}}{\partial\varphi_S^4}\right) - w^{(S)} + \frac{e_{11S}r_S}{C_{11S}^E}E_{\varphi S} + \frac{a_S}{h_S}q_{rS} = a_S\gamma_S\frac{\partial^2 w^{(S)}}{\partial t^2};$$

- equations of forced electrostatics for piezoceramics:

$$\vec{E}_S = -grad\,\psi_S;\ div\vec{D}_S = 0.\ S=1, 2. \qquad (3)$$

In expressions (1)−(3): j – is the number of the area of existence of the acoustic field; Δ – Laplace operator; $\Phi_j^{(s)}$ – the potential of the velocities of the S-th shell in the j-th region; k_j – the wave number of the medium in the j-th region; $u^{(S)}$ and $w^{(S)}$ – tangential and radial components of the vector of displacements of the points of the middle surface of the S-th shell; $\beta_S = h_S^2/12r_S(1+e_{31S}^2/C_{11S}^E\varepsilon_{33S}^{(S)})$; $a_S = r_S^2/C_{11S}^E$; q_{rS} – external radiation load of the S-th shell; C_{11S}^E, e_{31S}, ε_{33S}^S, γ_S – respectively, the modulus of elasticity at zero electric voltage, the piezoelectric constant, the dielectric constant at zero deformation, the density of the material of the S-th piezoceramic shell; $\vec{E}_S$ and $\vec{D}_S$ – vectors of voltage and induction of the electric field in the S-th shell.

To concretize these general equations, according to the physical formulation of the problem, they must be supplemented by the conditions of conjugation of acoustic fields at the boundaries of partial regions and shells and electrical conditions.

Conditions of conjugation of acoustic fields take the form:

$$\left.\begin{aligned}
&-\frac{\partial\Phi_1^{(1)}(k_1r_1,\varphi_1)}{\partial r_1} = \frac{\partial w^{(1)}}{\partial t},\ 0\le|\varphi_1|\le\pi,\ r_1 = r_1^{(1)} = r_{10}+\frac{h_1}{2};\\
&-\frac{\partial\Phi_2^{(1)}(k_2r_1,\varphi_1)}{\partial r_1} = \frac{\partial w^{(1)}}{\partial t},\ 0\le|\varphi_1|\le\pi,\ r_1 = r_2^{(1)} = r_{10}-\frac{h_1}{2};\\
&-\frac{\partial\Phi_2^{(2)}(k_2r_2,\varphi_2)}{\partial r_2} = \frac{\partial w^{(2)}}{\partial t},\ 0\le|\varphi_2|\le\pi,\ r_2 = r_2^{(2)} = r_{20}+\frac{h_2}{2};\\
&-\frac{\partial\Phi_3^{(2)}(k_3r_2,\varphi_2)}{\partial r_2} = \frac{\partial w^{(2)}}{\partial t},\ 0\le|\varphi_2|\le\pi,\ r_2 = r_2^{(2)} = r_{20}-\frac{h_2}{2};
\end{aligned}\right\} \qquad (4)$$

$$\left.\begin{aligned}
&\sigma_{r1} = -q_{r1} = -\left[p_1(k_1r_1^{(1)}) - p_2(k_2r_2^{(1)})\ \right],\ 0\le|\varphi_1|\le\pi;\\
&\sigma_{r2} = -q_{r2} = -\left[p_2(k_2r_1^{(2)}) - p_3(k_3r_2^{(2)})\ \right],\ 0\le|\varphi_2|\le\pi.
\end{aligned}\right\} \qquad (5)$$

Here σ_{r1} and σ_{r2} – the normal components of the tensors of mechanical stresses of the first and second shells of the transducer; $p_1 = -i\omega\rho_1\Phi_1(k_1r_1,\varphi_1)$, $p_2 = -i\omega\rho_2\Phi_2(k_2r_2^{(2)},\varphi_2)$, $p_3 = -i\omega\rho_3\Phi_3(k_3r_2^{(2)},\varphi_2)$ – acoustic pressures in the relevant areas.

The electrical boundary conditions consist in setting the electric field voltage in each of the piezoceramic shells and for their radial polarizations have the form:

$$E_{\varphi S} = -\frac{\psi_S}{h_S},\ S=1, 2. \qquad (6)$$

SOLVING THE PROBLEM OF DETERMINING PHYSICAL FIELDS

We present the displacement of the shells in the form of expansions into rows of the form:

$$u^{(S)} = \sum_n u_n^{(S)}e^{in\varphi_S};\ w^{(S)} = \sum_n w_n^{(S)}e^{in\varphi_s},\ S=1, 2. \qquad (7)$$

The acoustic potentials of the velocity in the regions j = 1, 2, 3 are represented by the expressions:

in the outer region (j = 1)

$$\Phi_1^{(1)}(k_1r_1,\varphi_1) = \sum_n A_n^{(1)}H_n^{(1)}(k_1r_1)e^{in\varphi_1}; \qquad (8)$$

in the inner region (j = 2) between the shells

$$\Phi_2^{(2)}(k_2r_2,\varphi_2) = \sum_m\left[B_m J_m(k_2r_2) + C_mN_{em}(k_2r_2)\right]e^{im\varphi_2}; \qquad (9)$$

in the inner region of the second shell (j = 3)

$$\Phi_3^{(2)}(k_3r_3,\varphi_2) = \sum_\chi D_\chi J_\chi(k_3r_2)e^{i\chi\varphi_2}. \qquad (10)$$

In the second partial region (j = 2) the field is represented in the local coordinates of the second (S = 2) shell. At the same time, the boundary conditions at the boundary $r_1 = r_2^{(1)}$ are given in the local coordinates of the first (S = 1) shell. The transfer of coordinate systems is carried out on the basis of addition theorems for cylindrical wave functions [11]. When $r_1 > l_{O_2O_1}$ we have:

$$J_m(k_2r_2)e^{im\varphi_2} = \sum_n J_{m-n}(k_2l_{O_2O_1})e^{i(m-n)\varphi_{O_2O_1}}J_n(k_2r_1)e^{in\varphi_1};$$

$$N_m(k_2r_2)e^{im\varphi_2} = \sum_n J_{m-n}(k_2l_{O_2O_1})e^{i(m-n)\varphi_{O_2O_1}}N_n(k_2r_1)e^{in\varphi_1}.$$

Then in the coordinates (r_1, φ_1) of the shell with the number $S = 1$ the field of the shell with the number $S = 2$ the field $\Phi_2(k_2 r_2, \varphi_2)$ will look like:

$$\Phi_2^{(2)}(k_2 r_1, \varphi_1) = \sum_m \sum_n \left[B_m J_n(k_2 r_1) + C_m N_n(k_2 r_1) \right] \text{x}$$

$$\text{x } J_{m-n}(k_2 l_{O_2 O_1}) e^{i(m-n)\varphi_{O_2 O_1}} e^{in\varphi_1} =$$

$$= \sum_m \sum_n \left[B_m J_n(k_2 r_1) + C_m N_n(k_2 r_1) \right] \Delta_{m-n}^{(2,1)} e^{in\varphi_1}, \qquad (12)$$

where $\Delta_{m-n}^{(2,1)} = J_{m-n}(k_2 l_{O_2 O_1}) e^{i(m-n)\varphi_{O_2 O_1}}$.

Algebraization of the system of functional equations (1)–(6) using relations (7)–(12) allows to obtain on the basis of the properties of completeness and orthogonality of functions $e^{in\varphi}$ on the interval $0 \le \varphi \le 2\pi$ the following infinite system of linear algebraic equations:

$$R_\vartheta^{(1)} w_\vartheta^{(1)} + \frac{\alpha_1}{h_1} i\omega \Big\{ \rho_1 A_\vartheta H_\vartheta(k_1 r_1^{(1)}) - \rho_2 \sum_m \left[B_m J_\vartheta(k_2 r_2^{(1)}) + \right.$$

$$\left. + C_m N_\vartheta(k_2 r_2^{(1)}) \right] \Delta_{m-\vartheta}^{(2,1)} \Big\} = \frac{e_{31,1}}{C_{11,1}^E} \cdot \frac{\psi_1}{2\pi h_1} \int_0^{2\pi} e^{i\vartheta\varphi_1} \partial\varphi_1;$$

$$w_\eta^{(1)} = -\frac{i}{c_1} A_n H_n^{(1)\prime}(k_1 r_1^{(1)});$$

$$w_\vartheta^{(1)} = -\frac{i}{c_2} \sum_m \left[B_m J'_\vartheta(k_2 r_2^{(1)}) + C_m N'_\vartheta(k_2 r_2^{(1)}) \right] \Delta_{m-\vartheta}^{(2,1)}; \quad (13)$$

$$R_n^{(2)} w_n^{(2)} + \frac{\alpha_2}{h_2} i\omega \Big\{ \rho_2 \left[B_n J_n(k_2 r_1^{(2)}) + C_n N_n(k_2 r_1^{(2)}) \right] -$$

$$- \rho_3 D_n J_n(k_3 r_2^{(2)}) \Big\} = -\frac{e_{31,2}}{C_{11,2}^E} \cdot \frac{\psi_2}{2\pi h_2} \int_0^{2\pi} e^{in\varphi_2} \partial\varphi_2;$$

$$w_n^{(2)} = -\frac{i}{c_2} \left[B_n J'_n(k_2 r_1^{(2)}) + C_n N'_n(k_2 r_1^{(2)}) \right];$$

$$w_n^{(2)} = -\frac{i}{c_3} D_n J'_n(k_3 r_2^{(2)}); \quad \vartheta = -\infty, 0, \infty; \quad n = -\infty, 0, \infty.$$

In expressions (13) we have:

$$R_\tau^{(S)} = \frac{\tau^2 (1 + \beta_S \tau^2)^2}{\tau^2 (1 + \beta_S \tau^2) - \alpha_S \gamma_S \omega^2} - \left[1 + \beta_S \tau^4 - \alpha_S \gamma_S \omega^2 \right], S = 1, 2;$$

τ takes the value n and ϑ;

$\Delta_{m-\vartheta}^{(2,1)} = J_{m-\vartheta}(k_2 l_{O_2 O_1}) e^{i(m-\vartheta)\varphi_{O_2 O_1}}$; «bar» means a derivative of a function by argument r.

The solution of an infinite system (13) of linear algebraic equations by the method of reduction or the method of successive approximations allows to determine with a given accuracy the quantitative values of the decomposition coefficients of the physical fields of the investigated hydroacoustic transducer and then the quantitative values of these fields. The calculated expressions for obtaining quantitative values are as follows.

For mechanical fields of a hydroacoustic transducer with dynamically controlled parameters, the oscillating velocities of its piezoceramic shells are determined by the relations:

- for the speed of radial oscillations $\frac{\partial w^{(S)}}{\partial t} = -i\omega w^{(S)}$;
- for the speed of tangential oscillations $\frac{\partial u^{(S)}}{\partial t} = -i\omega u^{(S)}$,

where $w^{(S)}$ and $u^{(S)}$ are described by expressions (7).

For the acoustic fields of the investigated transducer, the sound pressure on the surface of the outer shell is determined by expression (8) and on the outer surface of the inner shell – by expression (9).

The electric excitation currents $J^{(S)}$ of the shells can be calculated for shells with radial polarization according to the relations [12]:

$$J^{(S)} = \int_{S_{el}} \frac{\partial D_{rS}}{\partial t} dS_{elS};$$

$$J^{(S)} = i\omega \int_0^{2\pi} \left[-\varepsilon_{33S} \frac{\psi_S}{h_S} + \frac{e_{31S}}{r_{0S}} \Big(\sum_n n u_n^{(s)} e^{in\varphi_S} + \right.$$

$$\left. + \sum_n w_n^{(s)} e^{in\varphi_S} \Big) \right] r_{0S} d\varphi_S.$$

Here S_{elS} is the area of the cylindrical surface of the electrode of unit length of S-th shell; ∂D_{rS} – radial component of electrical induction of the S-th shell.

CONCLUSIONS

It is shown that in determining the analytical relations that describe the physical fields of a cylindrical piezoceramic hydroacoustic transducer when excited by a dynamically controlled signal from the electrical side, the nature of the polarization of the applied piezoelectric elements is of fundamental importance. By the method of bound fields in multiconnected domains taking into account the connectivity of physical fields in piezoceramic media during energy conversion and acoustic interaction of shells forming a transducer, calculated expressions are obtained that allow to quantify the dependences of electric, mechanical and acoustic fields at operative change of amplitudes and phases of electric voltages of excitation of piezoceramic covers of the hydroacoustic transducer.

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ФІЗИЧНІ ПОЛЯ ДИНАМІЧНО КЕРОВАНОГО ГІДРОАКУСТИЧНОГО ВИПРОМІНЮВАЧА З РАДІАЛЬНОЮ ПОЛЯРИЗАЦІЄЮ

Тенденція зниження робочих частот гідроакустичних станцій, при збереженні їх направлених властивостей, їх багатофункціональність і відсутність можливостей збільшення розмірів корабельних відсіків, в яких розміщуються гідроакустичні антени, змушує здійснювати пошук шляхів динамічного управління параметрами гідроакустичних антен і утворюючих їх перетворювачів. Оскільки гідроакустичні перетворювачі являють собою електромеханічні коливальні системи, що утворюються із двох зв'язаних між собою в єдиній конструкції частин – електричної та механічної, то для технічної реалізації задачі динамічного управління параметрами перетворювачів необхідно використовувати саме електричну частину. При побудові п'єзокерамічних гідроакустичних перетворювачів з динамічно керованими параметрами з електричної сторони характер поляризації п'єзокерамічних елементів відіграє важливу роль. Але для визначення кількісно цієї ролі в залежності від того, яку поляризацію – радіальну чи окружну мають п'єзоелементи перетворювача, необхідні відповідні розрахункові співвідношення. Показано, що при визначенні аналітичних співвідношень, які описують фізичні поля циліндричного п'єзокерамічного гідроакустичного перетворювача при його збудженні динамічно керованим сигналом з електричної сторони, характер поляризації застосованих п'єзоелементів набуває принципово важливого значення. Методом зв'язаних полів в багатозв'язних областях з урахуванням зв'язаності фізичних полів в п'єзокерамічних середовищах при перетворенні енергії і акустичної взаємодії оболонок, утворюючих перетворювач, одержані розрахункові вирази, що дозволяють кількісно оцінити залежності параметрів електричних, механічних і акустичних полів при оперативній зміні амплітуд і фаз електричних напруг збудження п'єзокерамічних оболонок гідроакустичного перетворювача.

Ключові слова: *п'єзокерамічний перетворювач, радіальна поляризація, динамічне електричне збудження.*

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