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Cylindrical Piezoceramic Radiator as a Complex Dynamic System

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A cylindrical piezoceramic sound emitter, formed by two coaxial thin piezoceramic spaced-apart shells with circumferential polarization and an elastic medium between them, is considered as a dynamic system with parameters operationally controlled from the electrical side during performance. Taking into account the interconnection of the electric, mechanical, and acoustic fields of the shells during the energy conversion of the energy exchange between the shells inside the emitter, when forming the acoustic field, the calculated relationships to determine the physical fields of the emitter under the dynamic control and the interconnectedness of the energy conversion processes as well as its formation in space by electric fields parameters of field's shells are obtained. It is shown that the quantitative characteristics of the dynamic behavior of the emitter depend on the ratio of the magnitudes of the electrical voltages supplied to the piezoceramic shells, the phase difference between them, the size of the shells and their materials electrophysical parameters, as well as physical parameters of the media filling the shells. A method of numerical analysis revealed the behavior of the emitter's physical fields when changing the shells' electrical excitation voltages and the phase difference between them for the case when the frequencies of the main form of mechanical vibrations of both shells in vacuum are the same. At the same time, a number of properties important for practical application of such emitters were established. The control of the amplitudes and phases of the exciting envelope of electrical voltages allows to: significantly increase the acoustic efficiency of the emitter and significantly expand the frequency range of its resonant sound emission without increasing the overall dimensions of the emitter; provide operational control of the emitter shells' mechanical fields, bringing their particle velocities to the maximum possible in terms of maintaining emitter's mechanical strength; to determine the laws of electric fields radiation of the emitter during dynamic control of its performance taking into account the method of excitation of piezoceramic shells. A physical interpretation of the causes of these properties is given.

Keywords: Cylindrical piezoceramic radiator, Dynamic control from the electrical side, Physical fields.

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1. INTRODUCTION

The versatility of modern echolocation tools stipulates the need for dynamic control of their emitters' parameters. For piezoceramic electromechanical sound emitters, the possibility of their operational control during emitters operation is provided by the presence of the electrical side. However, the complexity of the physical processes that occur in this case necessitates the development of methods to describe them as dynamic systems. An electromechanical emitter is characterized as a device that provides, on the one hand, the conversion of one type of energy into other types, and on the other hand, the formation of converted energy in the emitter's surrounding environment. In this case, three types of interaction of existing processes can be distinguished. The first of them is determined by the interconnection of electric, mechanical and acoustic fields when the energy is converted in the piezoceramic medium of the emitter. The second type of interaction is associated with the process of multiple exchanges of the emitted and reflected sound waves between the structural elements of the emitter. And the third type of interaction is determined by the interconnectedness of the energy conversion processes in the emitter and its formation by the emitter in the surrounding environments. The stated features of the piezoceramic sound emitter performance are complemented by the need to change the design of its construction so that it provides the possibility of operational control of its parameters by electrical means during the operation of the emitter. Naturally, all this requires the development of new approaches to the description of the emitter as a dynamic system.

We should note that in the resources [1-11], the methods for controlling the parameters of emitters are conventionally divided into passive and active. Passive methods involve the use of acoustic screens, which can be [1-6] both external and internal. The results obtained using these passive methods are quite fully presented in works on cylindrical emitters shielded by external open ring layers [5, 6], and in works [5-11] on the same emitters, but with internal acoustic screens. The main disadvantage of these massive methods is that during the emitters' performance, the capabilities of their parameters' operational control are structurally complicated. This drawback is absent in active methods associated with the dynamic control of the emitter parameters using its electric field [2]. The application of these methods is associated with the replacement of the internal acoustic screen with a cylindrical piezoceramic shell excited by an electric field from its own electric generator.

The aim of this work is to develop one of the approaches to the description of the dynamic behavior of a cylindrical piezoceramic emitter, taking into account all the above interaction processes of different physical nature fields that arise during its performance.

2. STATEMENT OF THE PROBLEM AND DERIVING ANALYTICAL RELATIONS

Let us determine the dynamic behavior of a cylindrical piezoceramic sound emitter (see Fig. 1).

The emitter is formed by two cylindrical piezoceramic spaced-apart shells 1 and 2 with the aligned longitudinal axes. Each of the shells has medium radii r_1 and r_2, thicknesses h_1 and h_2, has circular polarization and is composed of M_1 and M_2 rigidly glued together piezoelectric segments. Electrically, in each shell segments are connected in parallel, and electrical voltages are applied to their flat lateral faces $\psi_1 = \psi_{01} \cdot e^{-i\omega t}$ and $\psi_2 = \psi_{02} \cdot e^{-i(\omega t - \varphi)}$, where ω is the frequency and φ is the phase shift between these voltages.

The converter is placed in a medium with wave impedance $\rho_1 c_1$, and the spaces between the shells and inside the second shell are filled with media with wave impedances $\rho_2 c_2$ and $\rho_3 c_3$ respectively, where ρ_j and c_j $(j = 1, 2, 3)$ are the density and speed of sound in the corresponding medium. The thickness of the shells is small compared to their radii.

In order to determine the analytical relationships describing the physical fields of the studied emitter in coordinate systems (see Fig. 1), it is necessary to carry out a joint solution to a system differential equations, including:

– Helmholtz equation describing the motion of media inside and outside the emitter:

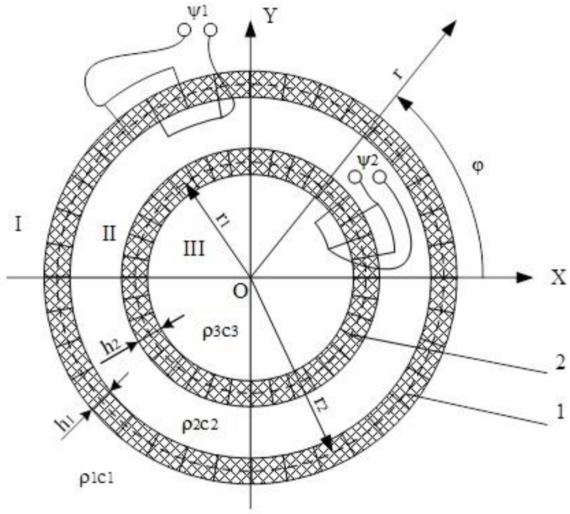


Fig. 1 – Normal section of a radiator

$$\Delta \Phi_j^{(s)} + K_j \Phi_j^{(s)} = 0\,; \tag{1}$$

– equation of motion of thin piezoceramic shells with circumferential polarization in displacements:

$$\begin{gathered}
(1+\beta_s)\frac{\partial^2 U_s}{\partial \varphi^2} + \frac{\partial W_s}{\partial \varphi} - \beta_s \frac{\partial^3 W_s}{\partial \varphi^3} = \alpha_s \gamma_s \frac{\partial^2 U_s}{\partial t^2}\,; \\
-\frac{\partial U_s}{\partial \varphi_s} + \beta_s \left(\frac{\partial^3 U_s}{\partial \varphi_s^3} - \frac{\partial^4 W_s}{\partial \varphi^4} \right) - W_s + \frac{e_{33s}}{C_{33s}^E} r_s E_{\varphi_s} + \frac{\alpha_s}{h_s} q_{rs} = \alpha_s \gamma_s \frac{\partial^2 W_s}{\partial t^2}\,;
\end{gathered} \tag{2}$$

– equations of forced electrostatics for piezoceramics:

$$\vec{E}_s = -grad\,\psi_s; \quad div\,\vec{D}_s = 0\,. \tag{3}$$

Here, s is the number of the piezoceramic shells in the emitter ($s = 1, 2$); j is the acoustic field number ($j = 1, 2, 3$); Δ is the Laplace operator; $\Phi_j^{(s)}$ is the velocity potential of the s-th shell in the j-th region; K_j is the medium wave number in the j-th region; U_s and W_s are the circumferential and radial components of the middle surface points displacement vector of the s-th shell; $\beta_s = h_s^2 / 12 r_{0s}\left(1 + e_{33s}^2 / C_{33s}^E \varepsilon_{33s}^{(s)}\right)$; $\alpha_s = r_s^2 / C_{33s}^E$; q_{rs} is the external radiation load of the s-th shell; C_{33s}^E, e_{33s}, ε_{33s}^s, γ_s are respectively the elastic modulus at zero electric tension, piezoelectric constant, dielectric constant at zero deformation, material density of the s-th piezoceramic shell; $\vec{E}_s$ and $\vec{D}_s$ are the intensity and induction vectors of the electric field in the s-th shell.

Analysis of the structure of the studied emitter clearly shows that its electrical and acoustic loads have radial symmetry. Therefore, the mechanical fields of the emitter shells will have [2, 3] only zero modes W_{01} and W_{02} of their radial displacements. Given this feature of the shells' mechanical fields, expressions (2) are transformed to:

$$\alpha_s \gamma_s \frac{\partial^2 W_s}{\partial t^2} + W_s = \frac{e_{33s}}{C_{33s}^E} r_s E_{\varphi_s} + \frac{\alpha_s}{h_s} q_{rs}, \quad s = 1, 2\,. \tag{4}$$

To solve the problem of dynamic behavior during sound emission by the given emitter, we divide the entire multiply connected region of the existence of its acoustic field into partial regions. The conditions for conjugation of fields at the interfaces between regions and shells can be written as:

$$\begin{gathered}
-\frac{\partial \Phi_1(k_1 r, \varphi)}{\partial r} = \frac{\partial W_{01}}{\partial t},\ 0 \le |\varphi| \le \pi;\ r = r_{11} = r_1 + \frac{h_1}{2}; \\
-\frac{\partial \Phi_2(k_2 r, \varphi)}{\partial r} = \frac{\partial W_{01}}{\partial t},\ 0 \le |\varphi| \le \pi;\ r = r_{12} = r_1 - \frac{h_1}{2}; \\
-\frac{\partial \Phi_2(k_2 r, \varphi)}{\partial r} = \frac{\partial W_{02}}{\partial t},\ 0 \le |\varphi| \le \pi;\ r = r_{21} = r_2 + \frac{h_2}{2}; \\
-\frac{\partial \Phi_3(k_3 r, \varphi)}{\partial r} = \frac{\partial W_{02}}{\partial t},\ 0 \le |\varphi| \le \pi;\ r = r_{22} = r_2 - \frac{h_2}{2}. \\
\sigma_{r_1} = -q_{r_1} = -\left[p_1(k_1 r_{11}) - p_2(k_2 r_{12})\right],\ 0 \le |\varphi| \le \pi; \\
\sigma_{r_2} = -q_{r_2} = -\left[p_2(k_2 r_{21}) - p_3(k_3 r_{22})\right],\ 0 \le |\varphi| \le \pi.
\end{gathered} \tag{5}$$

Here σ_{r_1} and σ_{r_2} are the normal components of the tensors of mechanical stresses of the first and second shells of the emitter; $p_1 = -i\omega\rho_1\Phi_1(k_1r,\varphi)$, $p_2 = -i\omega\rho_2\Phi_2(k_2r,\varphi)$, $p_3 = -i\omega\rho_3\Phi_3(k_3r,\varphi)$ are the acoustic pressures in the relevant areas.

The electric boundary conditions consist in setting the electric field strength in each of the piezoelectric ceramic shells, and for their circumferential polarizations they have the following form:

$$E_{\varphi_s} = -\frac{\psi_s M_s}{2\pi r_s}, \quad s = 1,2 . \tag{6}$$

Taking into account the above-described features of the mechanical fields of the emitter, the expressions for the velocity potentials of its acoustic fields in various partial regions can be written as:

$$\begin{aligned} &\Phi_1(k_1r,\varphi) = AH_0^{(1)}(k_1r); \\ &\Phi_2(k_2r,\varphi) = BJ_0(k_2r) + CN_0(k_2r); \\ &\Phi_3(k_3r,\varphi) = DJ_0(k_3r). \end{aligned} \tag{7}$$

When writing expressions for $\Phi_1(k_1r,\varphi)$ and $\Phi_3(k_3r,\varphi)$ Sommerfeld's conditions in the first partial region, the absence of field features in the third partial region, and traditional designations for the Hankel, Bessel, and Neumann functions are taken into account.

Algebraization of functional equations (1), (4) and (5) taking into account relations (6), (7) and the properties of completeness and orthogonality of angular functions systems, allows one to determine the unknown expansion coefficients (7) and obtain a system of linear algebraic equations of the form:

$$\begin{aligned} &W_{01}\left\{-\left(1-\alpha_1\gamma_1\omega^2\right)+\frac{\alpha_1}{h_1}\omega\rho_2c_2\left[-\frac{N_0'(k_2r_{21})}{N_0'(k_2r_{12})}\Delta_2+\frac{N_0(k_2r_{12})}{N_0'(k_2r_{12})}\right]-\frac{\alpha_1}{h_1}\omega\rho_1c_1\frac{H_0^{(1)}(k_1r_{11})}{H_0^{(1)\prime}(k_1r_{11})}\right\}+ \\ &+\frac{\alpha_1}{h_1}\omega\rho_2c_2\Delta_2W_{02} = \frac{e_{331}}{C_{331}^E}\frac{\psi_1M_1}{2\pi}; \\ &W_{01}\left\{\omega\rho_2c_2\frac{N_0'(k_2r_{21})}{N_0'(k_2r_{12})}\Delta_3\frac{\alpha_2}{h_2}-\frac{\alpha_2}{h_2}\omega\rho_2c_2\frac{N_0(k_2r_{21})}{N_0'(k_2r_{12})}\right\}+ \\ &+W_{02}\left\{-\left(1-\alpha_2\gamma_2\omega^2\right)+\frac{\alpha_2}{h_2}\omega\rho_3c_3\frac{J_0(k_3r_{22})}{J_0'(k_3r_{22})}-\frac{\alpha_2}{h_2}\omega\rho_2c_2\Delta_3\right\} = \frac{e_{332}}{C_{332}^E}\frac{\psi_2M_2}{2\pi}. \end{aligned} \tag{8}$$

where
$$\Delta_2 = \frac{J_0(k_2r_{12}) - J_0'(k_2r_{12})\dfrac{N_0(k_2r_{12})}{N_0'(k_2r_{12})}}{J_0'(k_2r_{12}) - J_0'(k_2r_{12})\dfrac{N_0'(k_2r_{21})}{N_0'(k_2r_{12})}};$$

$$\Delta_3 = \frac{J_0(k_2r_{21}) - J_0'(k_2r_{12})\dfrac{N_0(k_2r_{21})}{N_0'(k_2r_{12})}}{J_0'(k_2r_{21}) - J_0'(k_2r_{12})\dfrac{N_0'(k_2r_{21})}{N_0'(k_2r_{12})}},$$

«prime» denotes the derivative of the function with respect to the argument.

3. RESEARCH RESULTS

It is clear from physical considerations that the quantitative characteristics of the dynamic behavior of all physical fields i.e. acoustic, mechanical, and electric involved in the process of sound emission by a given type of cylindrical piezoelectric emitter depend on: the ratio of the magnitudes of the electrical voltages applied to the piezoceramic shells of the emitter; phase differences between these voltages; sizes of shells and electrophysical parameters of their materials; physical parameters of media filling the volumes between the shells and inside the second shell. Only the first two parameters out of them can provide dynamic control of the characteristics of this emitter.

Let us apply the obtained relations to evaluate the properties of the given type of the emitter as a dynamically controlled device.

As the investigated characteristics, we take the frequency dependences of the amplitudes of the electric, mechanical, and acoustic fields within a dynamic change of the parameters of the electric excitation of the emitter.

Electric current I_s calculations of the emitter excitation for external purposes of its external ($s = 1$) and internal ($s = 2$) piezoelectric shells were carried out according to the formula

$$I_s = S_{эл,s}\sum_{j=1}^{M_s}\frac{\partial D_{\varphi_s}^{(j)}}{\partial t},$$

where $S_{эл,s}$ is the electrode area per unit height of the s-th emitter shell applied to flat surfaces of the prisms; $D_{\varphi_s}^{(j)}$ is the electric induction of the j-th prism of the s-th emitter shell. In a cylindrical piezoceramic segmented shell with circumferential polarization [10], radial $D_{r_s}^{(j)}$, axial $D_{z_s}^{(j)}$ and circumferential $D_{\varphi_s}^{(j)}$ components of the electric induction in the given case are determined by the expressions:

$$D_{r_s}^{(j)} = D_{z_s}^{(j)} = 0;$$
$$D_{\varphi_s}^{(j)} = \varepsilon_{33s}^{(j)}E_{\varphi_s}^{(j)} + e_{33s}^{(j)}\frac{W_{0s}}{r_s}.$$

Then

$$\frac{\partial D_{\varphi_s}^{(j)}}{\partial t} = -i\omega\left[-\varepsilon_{33s}^{(j)}\frac{\psi_sM_s}{2\pi r_s} + \frac{e_{33s}^{(j)}}{r_s}W_{0s}\right].$$

Acoustic field pressures on the external ($s = 1$) surface of the emitter and external surface of its internal surface ($s = 2$) of the piezoelectric shell are determined by the relations:

$$p_1(r_{11}, 0) = -i\omega\rho_1 A H_0^{(1)}(k_1 r_{11}, 0);$$
$$p_2(r_{21}, 0) = -i\omega\rho_2 \left[B J_0(k_2 r_{21}, 0) + C N_0(k_2 r_{21}, 0) \right].$$

Particle velocities of external mechanical fields ($s = 1$) and internal ($s = 2$) piezoceramic shells of the emitter were calculated by the formulas:

$$\frac{\partial W_{01}}{\partial t} = -i\omega W_{01}; \quad \frac{\partial W_{02}}{\partial t} = -i\omega W_{02}.$$

The calculations were performed with the following characteristics of a dynamically excited emitter: aver-age external radii ($s = 1$) and internal ($s = 2$) piezoceramic shells $r_1 = 0.096$ m and $r_2 = 0.070$ m at thicknesses $h_1 = 0.004$ m and $h_2 = 0.003$ m and equal number of shell-forming prisms $M_1 = M_2 = 48$; regarding piezoceramic shell environments, TBC composition system was used for the external shell: $\rho_1 = 5400$ kg/m^3, $d_{331} = 113 \cdot 10^{-12}$ C/m^3; $C^E{}_{331} = 10.5 \cdot 10^{10}$ N/m^2; $\varepsilon^s{}_{331} = 10.4 \cdot 10^{-9}$ F/m; for the internal shell, the PZT composition system was used: $\rho_2 = 7200$ kg/m^3; $d_{332} = 320 \cdot 10^{-12}$ C/m^3; $C^E{}_{331} = 7.5 \cdot 10^{10}$ N/m^2; $\varepsilon^s{}_{332} = 19.5 \cdot 10^{-9}$ F/m; environments in the first, second and third areas, respectively $\rho_1 c_1 = \rho_2 c_2 = 1.5 \cdot 10^6$ kg/m^{2}s and $\rho_3 c_3 = 0$; amplitudes of exciting voltages $\psi_{01} = 200$ V, $\psi_{02} = 200$, 120, 0 V, phase shift (φ) between ψ_1 and ψ_2 equals to $\varphi = 0$, $\pi/2$, π, investigated frequency range from 0 to 35 kHz.

An analysis of the given frequency dependences makes it possible to establish complex qualitative and quantitative relationships between electronic, mechanical, and acoustic dynamic processes arising in piezoelectric ceramic media of a cylindrical emitter, and the influence of dynamic acoustic processes of sound-wave emission on them. First of all, let us pay attention to a number of physical features of the given emitter during its dynamic excitation. The electric fields of piezoceramic shells excitation of the emitter and the acoustic fields formed by these shells in the environments surrounding them are radially symmetric. This means that the electrical energy "ends" in the piezoelectric shells only with one form of their own vibrations – zero modes of the shells' mechanical fields. Therefore, each of the shells has one resonance of its own. The radiation of the acoustic waves of each of the shells in the space between them is the reason for the appearance of the acoustic interaction of the shells in it, which is conditioned by the multiple exchanges of the emitted and reflected waves between the shells. The acoustic field, formed in this case in the second region, continues to remain radially symmetric, but becomes dependent on a number of physical parameters of the emitter. These include: the values of the natural resonant frequencies of the shells and the distances between the internal surface of the external shell of the emitter and the external surface of the internal shell; physical parameters of media in all considered areas; the relationship between the amplitudes of the electrical voltages exciting the piezoelectric shell of the emitter, as well as the phase shift between them. The last two factors provide the possibility of operational control of the emitter's performance parameters. In order to exclude the influence of different values of the natural resonant frequencies of the emitter shells, when studying their sizes and compositions of piezoceramic materials, they were chosen so that these frequencies were the same. In this case, the values of these frequencies were 7.3 kHz.

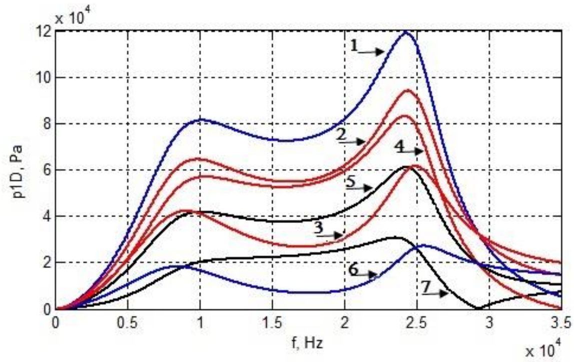
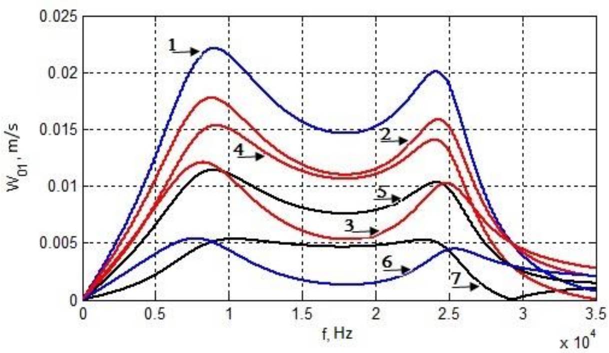
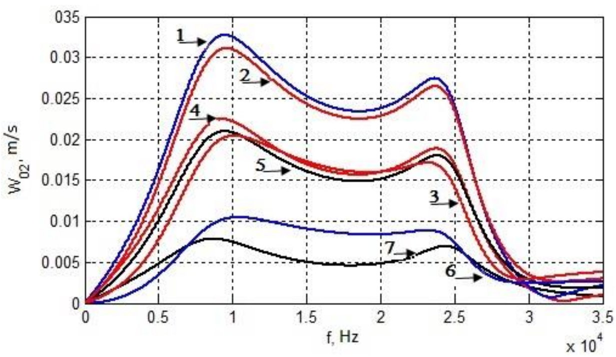


Fig. 2 – Frequency dependences of the pressure amplitudes of the acoustic field in the far zone of the dynamically excited emitter at $\psi_{02}/\psi_{01} = 1.0$ (1-3); $\psi_{02}/\psi_{01} = 0.6$ (4-6); $\psi_{02}/\psi_{01} = 0$ (7); $\varphi = 0$ (1, 4, 7); $\varphi = \pi/2$ (2, 5, 7); $\varphi = \pi$ (3, 6, 7)



a



b

Fig. 3 – Frequency dependences of the particle velocity amplitudes of the mechanical fields of external (a) and internal (b) shells of the dynamically excited emitter at $\psi_{02}/\psi_{01} = 1.0$ (1-3); $\psi_{02}/\psi_{01} = 0.6$ (4-6); $\psi_{02}/\psi_{01} = 0$ (7); $\varphi = 0$ (1, 4, 7); $\varphi = \pi/2$ (2, 5, 7); $\varphi = \pi$ (3, 6, 7)

Analysis of the reduced frequency characteristics of all three parameters of the given emitter's physical fields during its dynamic excitation (see Fig. 2-Fig. 5) indicates the resonance nature of these dependences. A common feature of the amplitude of frequency dependences of acoustic pressure (Fig. 2), particle velocity (Fig. 3) and the dynamic component of the electric current (see Fig. 5b) is the presence of two maxima spaced in frequency and a dip between them.

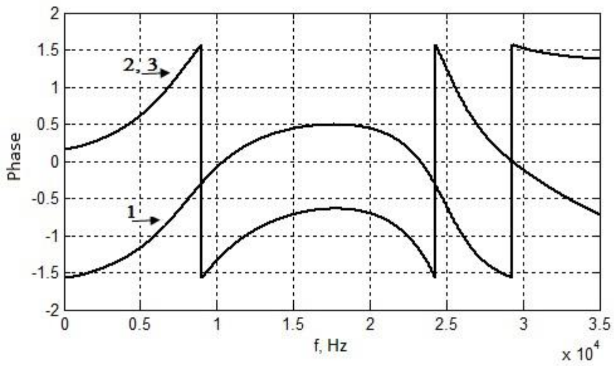
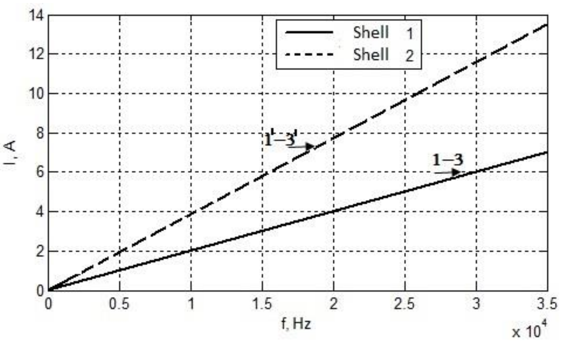
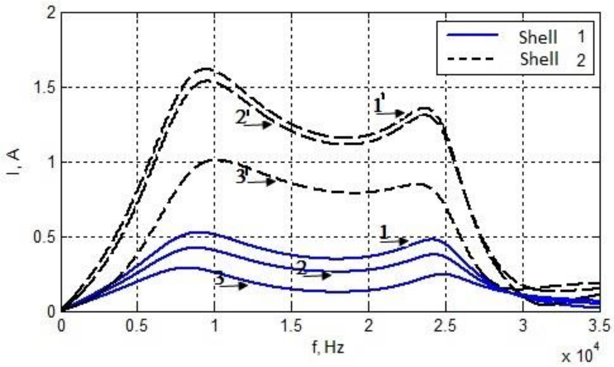


Fig. 4 – Frequency dependences of the particle velocity phases of the mechanical fields of the external shell of a dynamically excited emitter at $\psi_{02}/\psi_{01} = 1.0$; $\varphi = 0$ (1); $\varphi = \pi/2$ (2); $\varphi = \pi$ (3)



a



b

Fig. 5 – Frequency dependences of the capacitive (a) and dynamic (b) components of the total excitation current of the external and internal (dashed curves) piezoelectric shells of the dynamically excited emitter at $\psi_{02}/\psi_{01} = 1.0$; $\varphi = 0$ (1); $\psi_{02}/\psi_{01} = 1.0$; $\varphi = \pi/2$ (2); $\psi_{02}/\psi_{01} = 1.0$; $\varphi = \pi$ (3)

Moreover, as follows from the analysis of the phase characteristics of the mechanical field (see Fig. 4), the resonant frequencies of the lower maximum amplitudes of the particle velocities of the external and internal piezoelectric shells of the emitter (see Fig. 3, Fig. 4) slightly exceed resonant frequencies of these shells in vacuum with a slight excess for the outer shell. The resonant frequencies of the upper maximum values of these amplitudes of the mechanical field differ from the natural resonant frequency of each of the emitter shells by more than 3 times (see Fig. 4). In this case, the internal shell has higher values of the frequency of this resonance. A common feature of the above frequency characteristics of all physical fields is their significant dependence on both the ratio of the amplitudes of the voltages exciting the piezoceramic shells of the emitter and the phase difference between them.

Let us now analyze the features of the frequency dependences of each of the fields under dynamic excitation of the emitter.

Analysis of the amplitudes of the acoustic field in the far zone of the emitter (see Fig. 2) shows that in the absence of a phase shift (curves 1, 4, 7) in the pressure frequency range under consideration $p_D = |-i\omega\rho_1 A|$ increases close to the proportional law with respect to the growth of ψ_{02}/ψ_{01}. In this case, the shape of the frequency dependencies changes slightly. By the phase shift φ one can control the depth of the dip between the maximum values of the pressure amplitudes and the frequency shift of the second maximum resonance. The smallest dip occurs in the absence of a phase shift between exciting voltages.

An interesting property of a cylindrical emitter with dynamic control is a significant (more than 6-7 times) extension of its frequency band of resonant radiation as compared to a single external piezoceramic shell. It is this property that is of considerable practical interest.

Analysis of the frequency dependences of the mechanical field of the emitter (Fig. 3, Fig 4) shows that the behavior of both the amplitudes and phases of the vibrational velocities of the external and internal piezoceramic shells of the emitter is the same. The difference is only in their quantitative values. The latter is explained not only by various conditions of the acoustic voltage of the shells in the emitter, but also by the energy efficiency of converting electrical energy into mechanical energy, since the shells are made of various compositions of piezoceramic material. The established differences in the quantitative effect on the spectral properties of the external and internal piezoceramic shells of the emitter placement conditions have a clear physical explanation. Reactions of the external environment and the volume between the shells act on the external shell of the emitter. Changes in the latter between oscillating shells can occur only due to the compression of the medium between the shells. It is this that determines the elastic character of the resistance of the fluid filling the cavity between them and, as a result, the growth of the natural frequencies of the mechanical vibrational system of the external shell. The same nature of the spectral behavior of a mechanical field imposes a volume between the shells on the inner shell of the emitter, all the more so because its sound emission into its internal cavity is absent. In the region between the first and second resonant amplitudes bursts of the shells' particle velocities of the emitter, multiple energy exchange between the vibrating shells along the acoustic field in the internal volume between these shells plays an important role. In turn, the efficiency of this exchange is determined by the ratio of exciting stresses ψ_{02}/ψ_{01} and phase difference between them. This is exactly what the curves demonstrate (Fig. 3). From their comparison, it can be seen that at almost all frequencies the vibrational velocities of the inner shell are 1.5-2 times higher than those of the outer one. This is explained by the fact that the efficiency of the piezoceramic compositions of the PZT system is almost 2 times higher with respect to the compositions of TBC.

Analysis of the frequency dependences of the electric field (Fig. 5) allows us to establish the following. The total electric currents of excitation of the piezoelectric shells of the emitter are the sum of two currents – capacitive and dynamic. The first is determined by the bias currents in the piezoelectric media of the shells as specific capacitors and linearly depends on the frequency. The second is the result of the effect of electrostriction inherent in piezoceramic media. In the present case, the cylindrical piezoceramic shells of the emitter are excited by a radially symmetric electric field. Due to this, electric energy is "pumped" into the mechanical fields of the cylindrical shells of the emitter only at zero modes of their oscillations. Therefore, the partial dependences of the dynamic currents (Fig. 5) of the emitter's piezoceramic shells in their form repeat the frequency dependences of the particle velocities (Fig. 3) of these shells. Naturally, the patterns of operational control of the emitter's mechanical fields parameters with the help of appropriately selected excitation voltages of the emitter's shells and the phase difference between them also occur for the electric fields of piezoceramic shells of the emitter.

4. CONCLUSIONS

The above analysis indicates that a cylindrical piezoceramic sound emitter, formed by two coaxially spaced piezoceramic shells and an elastic medium between them, refers to dynamic devices whose parameters can be quickly controlled during operation from the electrical side.

A quantitative analysis of the acoustic, mechanical, and electric fields of the emitter with dynamic control allows us to establish the following features of the dynamic connections between them. Firstly, due to the controlled exchange of acoustic energy between the external and internal piezoceramic shells of the emitter in the internal cavity, the acoustic efficiency of the emitter is significantly increased between them and the frequency range of effective sound emission is significantly expanded without increasing the overall dimensions of the emitter. Secondly, by changing the exciting electric voltages of the piezoceramic shells and the phase difference between them, one can quickly control the mechanical fields of the shells by changing the resonant frequencies of the emitter, the bands of its resonant radiation and the amplitude of the particle velocities of the shells, bringing them closer to the maximum possible from the point of view of preservation of the mechanical strength of the shells. Thirdly, taking into account the interconnection of all the physical fields involved in the emission of sound and the method of electrical excitation of the shells, the laws governing the change of electric fields are determined, which provide dynamic control of the emitter's performance parameters. The established features of the dynamic processes occurring during sound emission must be taken into account when designing the emitting paths of echolocation systems.

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Циліндричний п'єзокерамічний випромінювач як складна динамічна система

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Циліндричний п'єзокерамічний випромінювач звуку, утворений з двох коаксіальних рознесених в просторі тонких п'єзокерамічних оболонок з окружною поляризацією і пружним середовищем між ними, розглянуто як динамічна система з параметрами, оперативно керованими в процесі роботи з електричного боку. З урахуванням взаємного зв'язку електричних, механічних і акустичних полів оболонок в процесі перетворення енергії та обміну енергією між оболонками всередині випромінювача при формуванні акустичного поля отримані розрахункові співвідношення для визначення фізичних полів випромінювача при динамічному управлінні і пов'язаності між собою процесів перетворення енергії і формування її в просторі параметрами електричних полів його оболонок.

Показано, що кількісні характеристики динамічної поведінки випромінювача залежать від відношення величин, що підводяться до п'єзокерамічних оболонок електричних напруг, різниці фаз між ними, розмірів оболонок і електрофізичних параметрів їх матеріалів, фізичних параметрів середовищ, що заповнюють оболонки. Методом чисельного аналізу виявлені особливості поведінки фізичних полів випромінювача при зміні електричної напруги збудження оболонок і різниці фаз між ними для випадку, коли частоти основної форми механічних коливань обох оболонок у вакуумі однакові. При цьому встановлено ряд важливих для практичного застосування властивостей таких випромінювачів. Управління амплітудами і фазами збуджуючих оболонки електричних напруг дозволяє: істотно підвищити акустичну ефективність випромінювача і значно розширити діапазон частот його резонансного випромінювання звуку без збільшення габаритних розмірів випромінювача; забезпечити оперативне управління механічними полями оболонок випромінювача, наближаючи коливальні швидкості їх до максимально можливих з точки зору збереження механічної міцності випромінювача; визначити закономірності випромінювання електричних полів випромінювача при динамічному управлінні його роботою з урахуванням способу збудження п’єзокерамічних оболонок. Дано фізичне трактування причин виникнення цих властивостей.

Ключові слова: Циліндричний п'єзокерамічний випромінювач, Динамічне управління з електричного боку, Фізичні поля.