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Calculations of Electric Fields of Circular Screened Systems, Generated from Cylindrical Piezoceramic Radiators

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Analytical relations, describing the electrical fields of cylindrical piezoceramic radiators with circular polarization as a member of the cylindrical systems with the baffle in the inner cavity, using the related fields method in multiply connected regions were obtained. Comparative analysis of the results of numerical experiments performed on the frequency characteristics of the electric field of the radiating systems for different modes of radiation allow to establish a number of subtle effects of the formation of the electric field of radiators.

Keywords: electric fields; circular system with baffle; piezoceramic cylindrical radiator; circular polarization.

1. Introduction

A piezoceramic radiator falls under the category of radio-electronic devices characterized by a particular feature. The radiator of this kind combines two interconnected parts, electrical and mechanical.

In the performance of project works, the electrical part of a piezoceramic radiator is represented as a design model with lumped parameters, whereas the mechanical part is a model with distributed parameters (Aronov, 2005; 2006). The connection between the electrical and the mechanical parts is established by means of an electromechanical transformer (Didkovskyi *et al.*, 2006; Oishi *et al.*, 2007).

In the meantime, in the course of projecting radio-electronic devices of echo sounder systems, use is made of the representation of piezoceramic radiators, or their systems, as equivalent electrical circuits. The main difficulty in designing such system is to determine the parameters of the mechanical part of the radiators. It is the motional arm of the equivalent circuits, and its parameters are determined by the interrelation of three physical fields – an electrical, mechanical, and acoustical – in the course of radiation process. The existence of such interrelation preconditions difficulties of the theoretical statement and resolution of the task (Leiko *et al.*, 2000; Grinchenko *et al.*, 2013) of determining both the said fields and their frequency dependence, knowing which is especially important for the construction of adequate radiator equivalent circuits.

Two conditions emerge herein. The first is connected with the fact that the electric excitation of cylinder piezoceramic radiators is radially symmetric, owing to which electrical energy is "injected" into them only at the zero mode of the mechanical oscillations of radiators. The second condition is that including radiators into the system breaks the radial symmetry of their radiational acoustic load. As shown in the works (Korzhyk, 2011; Grinchenko *et al.*, 2013; Gusak, Leiko, 2016; Nyzhnyk, 2018) cylindric radiators with the broken symmetry of radiational acoustic load give way to new modes of their mechanical oscillations, which leads to the effective redistribution of energy "injected" into the radiators of the system at the zero mode between the new forms of their mechanical oscillations. As a result of the described effects, differing features in the physical fields of the radiators of the system may emerge (Vovk, 1992; Vovk *et al.*, 1994; Vovk, Oliynik, 1996).

The purpose of the article is to research those features as applied to the electrical fields of cylindrical piezoceramic radiators constituting circular cylindrical systems with a cylindrical acoustic baffle in the system's inner cavity.

2. Main part

Let us determine the electrical fields of radiators constituting the circular cylindrical system with a cylindrical acoustic baffle in the system's inner cavity. The system, the normal section of which is shown in Fig. 1, consists of N parallel circular cylindrical radiators (1) and an acoustically soft baffle (2).

The radiators, with the average radius r_{0S} and thickness h_S ($S = 1, ..., N$), are formed from M_S electrically shunt piezoceramic prisms with circumferential polarization, firmly bonded to each other. Harmoniously time-controlled voltage $\psi_S = \psi_{0S} e^{-i\omega t}$ with the frequency ω (i is an imaginary unit) is channelled to the electrodes of the prisms. The inner cavity of the constructions of the radiators is filled with an environment with the density ρ_S and the acoustic velocity c_S. The system of the radiators, with their X-axes positioned alongside the circle with the radius R_0, and the baffle with the inner radius r_{0N+1} are located in the environment with the density ρ and the acoustic velocity c. The coordinates systems used to solve the problem are shown in Fig. 1.

The electrical fields of piezoceramic radiators of the circular cylindrical system with a baffle may be defined by the simultaneous solution of differential equation system consisting of:

- the equations of forced electrostatics for piezoceramics:

$$\mathbf{E}_S = -\text{grad}\,\psi_S; \qquad \text{div}\mathbf{D}_S = 0; \qquad S = 1, ..., N;$$

- the equations of the movement of thin piezoceramic layers of radiators with circular polarization in their displacements:

$$(1+\beta_S)\frac{\partial^2 u_S}{\partial \varphi_S^2} + \frac{\partial w_S}{\partial \varphi_S} - \beta_S \frac{\partial^3 w_S}{\partial \varphi_S^3} = a_S \gamma_S \frac{\partial^2 u_S}{\partial t^2},$$

$$-\frac{\partial u_S}{\partial \varphi_S} + \beta_S\left(\frac{\partial^3 u_S}{\partial \varphi_S^3} - \frac{\partial^4 w_S}{\partial \varphi_S^4}\right) - w_S + \frac{\varepsilon_{33S}\, r_{OS}}{C_{33S}^E} E_{\varphi S} \qquad (1)$$

$$+\frac{a_S}{h_S} q_{rS} = a_S \gamma_S \frac{\partial^2 w_S}{\partial t^2}; \qquad S = 1, ..., N;$$

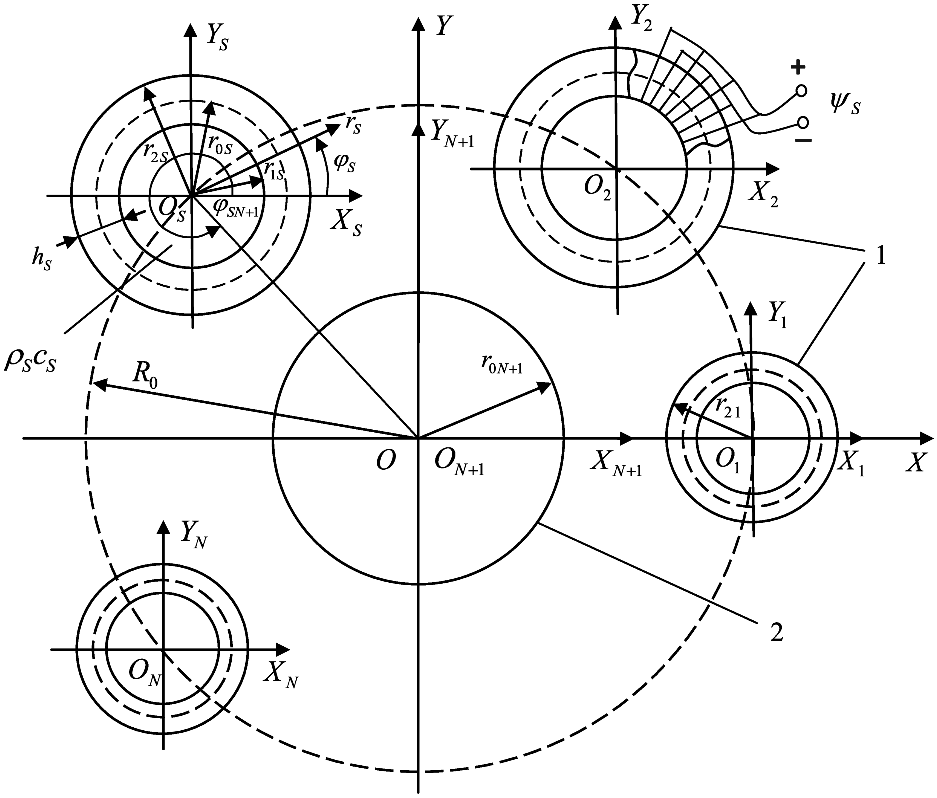

Fig. 1. Normal section of the cylindrical system of radiators with a baffle.

- the Helmholtz equation, describing the movement of environments inside and outside the radiators of the system and outside its baffle:

$$\Delta\Phi_{iS} + k_{iS}^2\Phi_{iS} = 0; \qquad S = 1, ..., N;$$

where $\mathbf{E}_S$ and $\mathbf{D}_S$ are, respectively, the intensity and magnetic induction vectors of the electric field of the S-th radiator; Δ – the Laplasian operator; Φ_{iS} – the velocity potential of the S-th radiator inside $\Phi_{iS} = \Phi_{1S}$ and outside $\Phi_{iS} = \Phi_S$ the radiator; k_{iS} – the wave number of environments inside ($k_{iS} = k_{1S}$) and outside ($k_{iS} = k$) the S-th radiator; u_S and w_S, respectively, the circular and radial components of the vector of translation of middle surface points of the piezoceramic layer of the S-th radiator; $\beta_S = \frac{h_S^2}{12r_{0S}^2}\left(1 + \frac{e_{33S}^2}{C_{33S}^E\varepsilon_{33S}^0}\right)$; $a_S = r_{OS}^2/C_{33S}^E$; q_{rS} – the inner load of the S-th radiator; C_{33S}^E, ε_{33S}^0, e_{33S}, respectively, the modulus of elasticity in zero electric intensity, the dielectric permittivity in zero deformation, and the density of the material of the piezoceramic layer of the S-th radiator of the system.

The acoustic boundary conditions include the Sommerfeld conditions, the condition of the absence of any features in the inner fields of all radiators of the system, as well as the condition on the surface of baffle $r_{2,\,N+1}$ in the following form:

$$\Phi(r_{N+1}, \varphi_{N+1}) = 0; \quad 0 \le \varphi_{N+1} \le 2\pi; \qquad r_{N+1} = r_{0\,N+1}; \tag{2}$$

where $\Phi(r_{N+1}, \varphi_{N+1})$ is the full acoustic field of the circular cylindrical system with a baffle in the surrounding environment, expressed in terms of the local coordinates of the baffle.

The electrical boundary conditions include:

- the expression of the intensity of the electrical field in the piezoceramic layer of each of $S = 1, ..., N$ radiators of the system in the following form:

$$E_{\varphi_S} = \frac{-\psi_{0S}M_S}{2\pi r_{0S}}; \tag{3}$$

- the determination, in accordance with (Gusak, Leiko, 2016), of the radial $D_{r_S}^{(j)}$, the axial $D_{z_S}^{(j)}$, and the circular $D_{\varphi_S}^{(j)}$ components of the electric induction for the j-th prism in the cylindrical piezoceramic layer of the S-th radiator with circular polarization by the following expressions:

$$D_{r_S}^{(j)} = 0, \qquad D_{z_S}^{(j)} = 0,$$
$$D_{\varphi_S}^{(j)} = \varepsilon_{33S}^{(j)}E_{\varphi_S}^{(j)} + e_{31S}^{(j)}(\varepsilon_{r_S}^{(j)} + \varepsilon_{z_S}^{(j)}) + e_{33S}^{(j)}\varepsilon_{\varphi_S}^{(j)}, \tag{4}$$

where $\varepsilon_{r_S}^{(j)} = \frac{\partial w_S}{\partial r_S}$; $\varepsilon_{z_S}^{(j)} = 0$, $\varepsilon_{\varphi_S}^{(j)} = \frac{1}{r_S}\frac{\partial u_S}{\partial \varphi_S} + \frac{w_S}{r_S}$; $e_{31S}^{(j)}$ – the piezo constant; $j = 1, ..., M_S$; $S = 1, ..., N$.

3. Deduction of design ratios

Let us now divide the whole multiconnected domain of the existence of physical fields of the circular system with a baffle into a range of finite domains (Fig. 1).

In such a case, in order to ensure the exhaustiveness, the system of the basic equations of the problem (1)–(4) should be extended with the kinematic and dynamic conditions of the conjunction of fields on the interface of the finite domains:

$$\begin{gathered}
-\frac{\partial\Phi_{1S}(r_S,\varphi_S)}{\partial r_S} = \frac{\partial w_S}{\partial t}, \\
r_S = r_{1S} = r_{0S} - \frac{h_S}{2}, \quad 0 \le |\varphi_S| \le \pi, \\
-\frac{\partial\Phi(r_S,\varphi_S)}{\partial r_S} = \frac{\partial w_S}{\partial t}, \\
r_S = r_{2S} = r_{0S} + \frac{h_S}{2}, \quad 0 \le |\varphi_S| \le \pi, \\
q_{r_S} = -\left(\frac{\rho\partial\Phi}{\partial t} - \frac{\rho_S\partial\Phi_{1S}}{\partial t}\right), \\
r = r_{0S}, \quad S = 1, ..., N, \quad 0 \le |\varphi_S| \le \pi,
\end{gathered} \tag{5}$$

where $\Phi = \sum\limits_{S=1}^{N+1}\Phi_S$ is the velocity potential of the full acoustic field, expressed in the local coordinates of the S-th radiator.

Let us express the mechanical (u_S and w_S) and acoustic (Φ_S and Φ_{1S}) fields of all $S = 1, ..., N$ radiators and screen $S = N + 1$ of the circular system in the form of the expression in terms of angular and wave functions of the circular cylinder:

$$u_S = \sum_n u_n^{(S)}\mathrm{e}^{in\varphi_S}, \qquad w_S = \sum_n w_n^{(S)}\mathrm{e}^{in\varphi_S}, \qquad S = 1, ..., N; \tag{6}$$

$$\begin{gathered}
\Phi_S = \sum_n A_n^{(S)}H_n^{(1)}(k\,r_S)\mathrm{e}^{in\varphi_S}, \quad S = 1, ..., N+1, \\
\Phi_{1S} = \sum_n B_n^{(S)}J_n(k_S\,r_S)\mathrm{e}^{in\varphi_S}, \quad S = 1, ..., N.
\end{gathered} \tag{7}$$

The Eq. (7) uses traditional designations of cylindrical functions. The unknown coefficients $u_n^{(S)}$, $w_n^{(S)}$, $A_n^{(S)}$, $B_n^{(S)}$, included there in, are deduced from the functional Eqs (1), the boundary conditions (2) and the conditions of the conjunction of fields (5). The necessary coordinate translation is conducted via addition theorems for cylindrical wave functions:

$$H_m^{(1)}(kr_q)e^{im\varphi_q} = \sum_n J_n(kr_S)H_{m-n}^{(1)}(kr_{qS}) \cdot \mathrm{e}^{i(m-n)\varphi_{qS}}\mathrm{e}^{in\varphi_S}, \tag{8}$$

where r_{qS} and φ_{qS} are the polar coordinates of the origin of the coordinate system O_S in the coordinates of the q-th system.

The algebraization of functional equations systems (1), (2), (5) by using Eqs (3), (6)–(8) and the properties of completeness and orthogonality of angular functions systems in the interval $[0, 2\pi]$ allows obtaining the infinite system of linear equations as mentioned in the work (Gusak, Leiko, 2016) in order to determine the unknown expansion coefficients (6) and (7).

Since the physical considerations (Fig. 1) make it clear that the existence in the system of the finite number of radiators and the acoustic baffle breaks the radial symmetry of their load by the acoustic field while preserving such a symmetry in the case of their load by the electrical field, the angular distributions of oscillations on the surface of the piezoceramic layers of the radiators of the system will be inconsistent. The result of this inconsistency is the respective fixed connection between the degree of electrical current exciting differing prisms of the layers of the radiators, and the angular position of those prisms in the radiators of the system. Given the foregoing, the equation

$$I_S = S_{el}^{(S)} \sum_{j=1}^{M_S} \frac{\partial D_{\varphi_S}^{(j)}}{\partial t}, \tag{9}$$

where $S_{el}^{(S)}$ is the electrode area of the piezoceramic prism of the S-th radiator for the electrical current I_S flowing in the excitation circuit of the S-th radiator of the system, may, after a number of transformations similar to those in the work (Gusak, Leiko, 2016) and subject to Eqs (3), (4), and (6), be put in the following form:

$$I_S = -\omega S_{el}^{(S)} \left\{ -\varepsilon_{33\,S}^{0} \frac{\psi_{0S} M_S^2}{2\pi r_{0S}} + \frac{e_{33\,S}}{r_{0S}} \sum_{j=1}^{M_S} \cdot \left[\sum_n i n u_{nS}\, \mathrm{e}^{in\frac{2\pi j}{M_S}} + \sum_n w_{nS}\, \mathrm{e}^{in\frac{2\pi j}{M_S}} \right] \right\}. \tag{10}$$

The input electrical resistances of the radiators of the system $Z_S = R_S + iX_S$ is determined in accordance with the Ohm's law.

4. Key findings

Let us apply the formulated equations to the quantitative estimation of the frequency responses of the parameters of the electrical field of the radiators of the system in question in two modes of its work – the circular radiation mode and the sectoral radiation mode, with its radiators being water-filled constructions.

The following parameter values of radiators, the system, and environments were used in calculations:

- the piezoceramics of the CTBS-3 composition with the density $\gamma = 7210\ \mathrm{kg/m^3}$; the piezo constant $e_{33} = d_{33} \cdot C_{33}^E$, where $d_{33} = 286 \cdot 10^{-12}$ C/N – the piezo module; the dielectric permittivity $\varepsilon_{33}^0 = 1280 \cdot 8.85 \cdot 10^{-12}$ F/m and the modulus of elasticity $C_{33}^E = 13.6 \cdot 10^{-10}\ \mathrm{N/m^2}$;
- the average radius of the piezoceramic layer $r_0 = 0.068$ m with the wall thickness $h = 0.008$ m and the number of prisms $M_S = 48$;
- the number of identical radiators in the system $N = 3$, with their positioning along the circle $R_0 = 0.147$ m, either evenly or in the sector ±60°;
- the outer radius of the baffle $r_{0N+1} = 0.072$ m;
- the exciting voltage $\psi_0 = 200$ V for all S;
- the environment for the filling of the external environment and the inner cavities of the radiators – water, $\rho c = 1.5 \cdot 10^6\ \mathrm{kg/m^2 s}$.

When calculating an infinite system of equations for determining, the unknown coefficients of expansions (6) and (7) have been solved using reduction method (Leiko *et al.*, 2000). The order of truncation of L infinite systems has been chosen on the basis of an estimate of the accuracy of satisfying the boundary conditions of the problem and thus $L = 50$ has been approved. And this ensured the equality of the vibrational velocities of the media particles and the displacement velocities of the shell surfaces of the emitters to an accuracy of 3%.

The results of the calculations of the frequency dependencies of the capacitive (curve 1) and the dynamic (curve 2) components of the electrical current I of piezoceramic radiators constituting the circular system with a baffle in the circular (a) and sectoral (b) radiation modes are shown in Fig. 2.

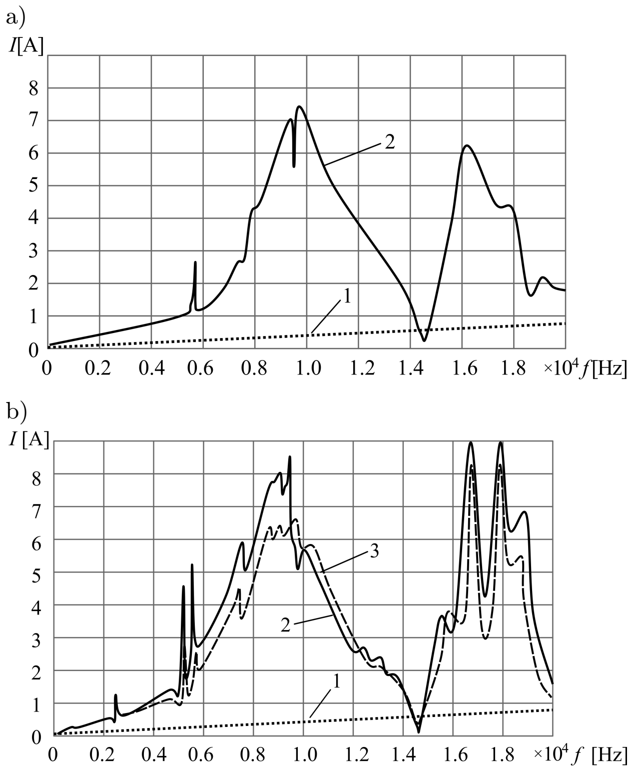

Fig. 2. The frequency dependences of the capacitive (curve 1) and dynamic (curve 2 for $S = 1$, curve 3 for $S = 2$) components of the electric current of piezoceramic radiators in the circular (a) and sector (b).

As appears from the analysis of Eq. (10), the electrical current in the outer circuit of the S-th radiator of the circular system with a baffle is the sum of two currents, the so-called capacitive and dynamic ones. The capacitive current is determined by the role of the piezoceramic radiator as a specific capacitor, and its degree is dependent on the composition of piezoceramics used in the radiator.

The dynamic current is the result of the connectedness of all three physical field in the course of the work of the radiator as part of the system in question, and its degree is determined by the degree of such connectedness. Their frequency dependencies are shown in Fig. 2. They reveal that in any modes of radiation (Fig. 2, curve 1) the capacitive currents of identical radiators in the circular system are equal for all radiators, and the dynamic currents (Fig. 2, curve 2) differ from each other both in differing modes and in the similar mode. Given this, the values of dynamic currents in the interval of frequencies being considered significantly exceed the values of capacitive currents.

The analysis of curves in Fig. 2a testifies to the fact that in the circular radiation mode of the system with a baffle, its radiators are excited by the same dynamic current. In the meantime, when the system transitions to the sectoral radiation mode (Fig. 2b), the nature of the conduct of the dynamic current of the radiators comes to be dependent on their positioning in the circular system with a baffle. In this case, the radiators positioned symmetrically in the sector have the same dynamic currents, and their frequency dependencies are considerably different, depending on how distant the radiators are from the symmetry line of the sector of the radiation of the system.

The results of the calculations of the frequency dependences of the active $\mathrm{Re}\,Z$ (a) and reactive $\mathrm{Im}\,Z$ (b) components of the input electrical resistance Z of piezoceramic radiators constituting the same system in the circular and sectoral radiation modes, respectively, are shown in Figs 3 and 4.

The analysis of the frequency dependencies of the input electrical resistances of the radiators of the circular system with a baffle (Figs 3 and 4) draws the attention to a number of interesting effects which may appear to be paradoxical.

Thus, the analysis of the curves in Fig. 3 shows that the active components of the input electrical resistances of the radiators become zero at particular frequencies. Furthermore, as suggested by the analysis of the curves in Fig. 4, the active components of the input electrical resistances of the radiators of the circular system with a baffle may even take negative values not only at particular frequencies but also in some intervals of frequencies.

This infers that in the case of the circular radiation (Fig. 3), when $R_S = 0$ at particular frequencies, the circular system does not consume the electrical

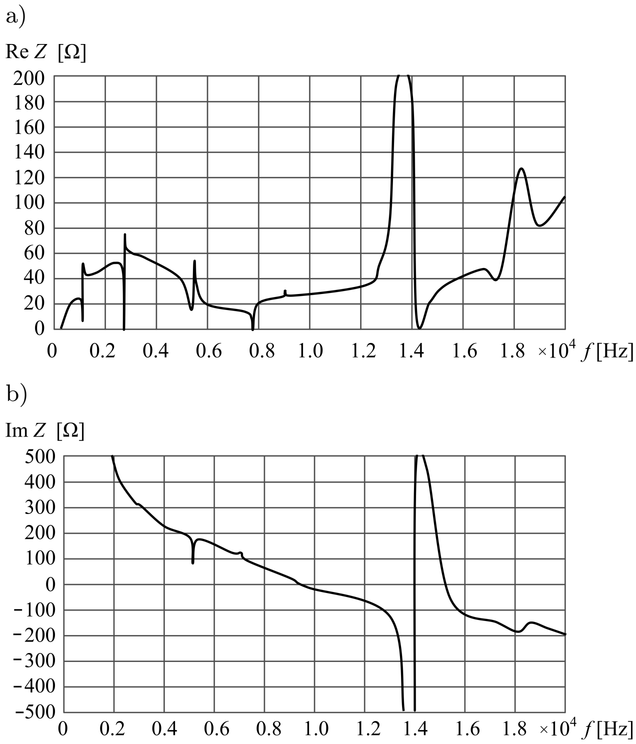

Fig. 3. Frequency dependences of the active Re Z (a) and reactive Im Z (b) components of the input electrical resistance Z of piezoceramic radiators in the circular radiation mode.

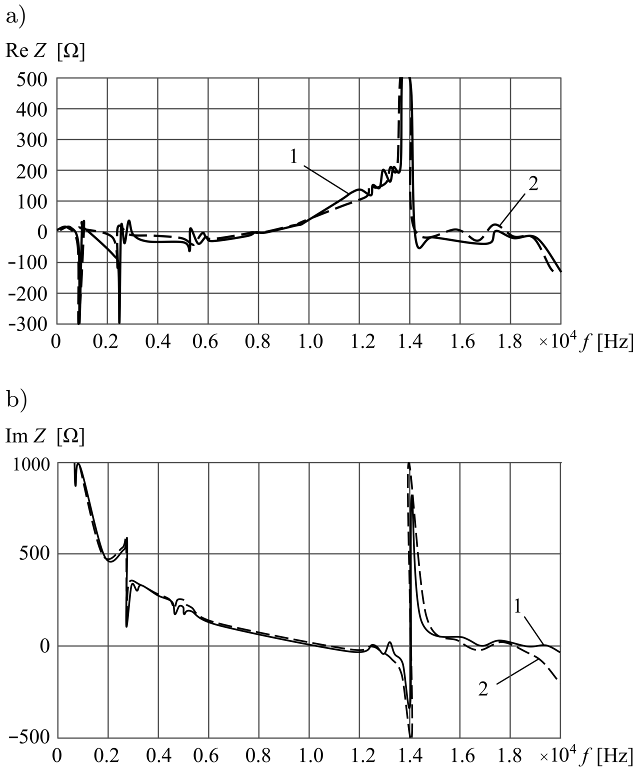

Fig. 4. Frequency dependences of the active Re Z (a) and reactive Im Z (b) components of the input electrical resistance Z of the piezoceramic emitters in the sector emission mode (curve 1 for $S = 1$, curve 2 for $S = 2$).

energy at such frequencies from the electronic devices that power the radiators. In the case of the sectoral radiation (Fig. 4), however, not only does the circular system not consume energy from the radiators excitation devices but also, on the contrary, with $R_S < 0$, gives up this energy back to those devices, thus becoming the energy producer rather than consumer in some intervals of frequencies. The complex nature of the frequency dependency is also characteristic of the reactive component of the input electrical resistances of the radiators of the circular system with a baffle both in the circular and in the sectoral radiation modes.

It is evident that the revealed effects may rather negatively affect the energetic efficiency of circular systems with a baffle and significantly complicate the consistency between piezoceramic radiators and the excitation electronic devices.

As has been noted earlier, the physical reasons for those effects are the radial symmetry of the electrical field of the radiators of the system, given the mode of the attachment of electrodes to the radiators' surfaces and the breaking of the radial symmetry of the acoustical fields, created by the radiators constituting the system with a baffle, due to multiple exchanges of radiated and scattered acoustical waves among all elements of the system. When a cylindrical piezoceramic radiator works beyond the system, its radially symmetric electrical field excites only a zero own form of mechanical oscillations in the mechanical field and the corresponding radially symmetric radiational acoustical field. The breaking of this symmetry of the acoustical field of the radiator as part of the system with a baffle leads, given the connectedness of all physical fields in the course of the work of the radiator, to the emergence of a succession of following modes in its mechanical field and the subsequent redistribution of energy "injected" into the radiator at zero mode among the components of the acoustical field, which correspond to all modes of oscillations of the mechanical field. At frequencies where the energy of the full acoustical field, created by all modes of oscillations, exceeds the energy radiated by the system at zero mode of mechanical oscillations, the reverse process emerges, whereby, due to the connectedness of the fields, this exceeding amount of energy of the acoustical field is returned, again, only at zero mode of the mechanical oscillations of the radiators in their electrical field.

In order to confirm assumptions, adopted in the solution of the problem under consideration and the numerical calculations, experimental studies of the electric current magnitude in the external circuit of electric excitation of the radiators of the circular system with the screen have been made as well as their comparison with the calculated data of the system. The type of the experimental model of the system (a) and the measuring stand (b) is shown in Fig. 5.

a)

b)

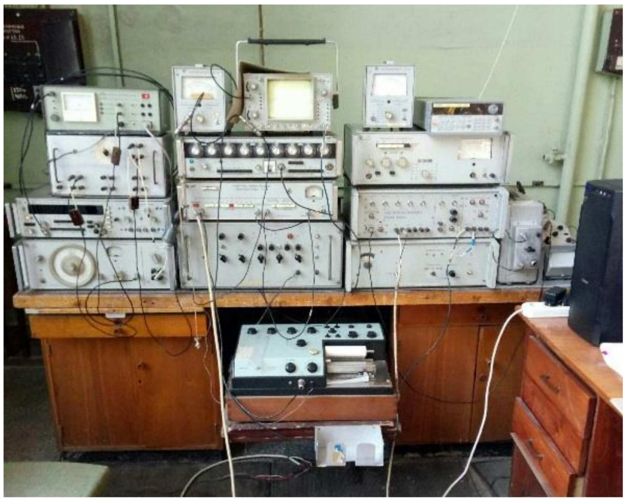

Fig. 5. Experimental layout (a) of a circular three-element system with a screen and a measuring stand (b).

The prototyping system is formed using two cylindrical piezoceramic radiators ($N = 2$), arranged in the form of a sector, and a cylindrical acoustically soft screen. All elements of the system have the same dimensions (diameter is 64.4 mm, length is 265 mm) and the same distance (5 mm) between their surfaces. Piezoceramic shells of radiators (8 mm thick) have circumferential polarization and they are composed of 30 rigidly glued piezoceramic prisms of CTBS-3 composition, and their internal cavities are vacuumized. Electric excitation was carried out with a voltage of 50 V at a number of frequencies. The measurements were carried out in a damped measuring hydroacoustic tank in accordance with the requirements of the state standard. The number of independent realizations of the measurements was 7, which provided the mean square error in measuring the frequency dependences of current amplitudes not worse than 0.24 at a confidence probability of 0.95. The standardize results of the calculations (curve 1), performed per unit length of the radiators according to the above mentioned formulas for sector radiation and numerical values, corresponding to the parameters of the three-element system model consisting of two vacuumized radiators placed as a sector, and the screen, and the experimental data (curve 2) are presented in Fig. 6.

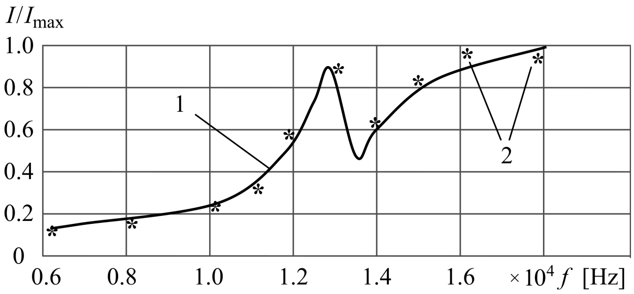

Fig. 6. Calculated (1) and experimental (2) frequency dependences of the electric current in the excitation circuit of the radiator $S = 1$ in a three-element system with a screen and sector radiation.

Their comparison allows us to conclude that the analytic relations obtained in the course of the work and the results of calculations correspond to the realities of the systems under study.

5. Conclusion

The application of the rigorous method of related fields in multiconnected domains has allowed calculating the design ratios for the quantitative estimation of the parameters of the electrical fields of the cylindrical piezoceramic radiators with circular polarization as part of circular systems with a baffle. Using numerical analysis of the frequency properties of electric fields has been shown that:

a) the capacitive components of the electrical current in all outer circuits of identical radiators of the system are equal, whereas the dynamic components significantly differ for the circular and sectoral radiation modes of the work of the system;

b) subject to certain conditions, particular radiators of the system with a baffle may translate into some other mode at particular frequencies, namely, from the mode of consuming electrical energy from the electronic devices of the echo sounder system into the mode of returning the energy to those devices due to the consumption of energy of the acoustic field from the external environment of the system.

It is evident that the revealed effects may rather negatively affect the energetic efficiency of circular systems with a baffle and significantly complicate the consistency between piezoceramic radiators and the excitation electronic devices. Therefore, by carefully choosing the parameters of the elements of the system with a baffle, as well as of the system itself, it is possible to control the characteristics of the electrical field of the system in order to achieve their necessary values.

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