UDC 623.983
DOI: https://doi.org/1034169/2414-0651.2021.2(30)66-72

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ACOUSTIC PROPERTIES OF THE DEEP SCREENED SONAR RADIATOR

The necessity of application of rigid type acoustic screens in hydroacoustic stations with deep-water antennas of variable depth is substantiated. By the method of coupled fields in multiconnected regions for antennas formed from cylindrical piezoceramic radiators with rigid screens in the form of open rings of finite thickness, analytical expressions for calculations of acoustic fields of such radiators are obtained. In the solution of the problem "pass-through" radiation shielded transducer included interactions: electrical, mechanical and acoustic fields in the conversion of energy; acoustic fields of the shell and screen during energy generation; processes of energy conversion and formation. Quantitative results of calculations of acoustic fields on the received expression are resulted.

Keywords*: cylindrical piezoceramic radiator, rigid screen, acoustic field.*

INTRODUCTION

The efficiency of the system "hydroacoustic station – surface ship" (HAS-SS) with variable depth antennas (VDA) largely depends on the horizon of the hydroacoustic antenna of HAS in the marine environment [1, 2]. This fact is the need to lower the antenna layer below the "jump", which is usually located at a sufficiently great depth [3].

Typically, HAS sonar antennas must have specified directional properties to meet the operational requirements for HAS in terms of range and resolution to detect underwater targets. Today, the creation of such properties, especially in the creation of radiating sonar antennas, is achieved by adding acoustic screens to the antennas. First, this is due to the corresponding simplicity of their structural and technological implementation in the form of sound-reflecting rubbers, foams or elastic metal shells [4, 5] and, second, their relatively low weight. In the latter case, the dependence of the acoustic properties of the screens on the depth of their immersion remains. This is a significant disadvantage of sonar antennas with acoustically soft screens, which limits or even eliminates their use in deep-sea VDA.

Hard type acoustic screens do not have this disadvantage. However, they also have their drawbacks.

First, a significant mass, the presence of which complicates the design of VDA and their operation.

Second, the complexity of constructions in the form of solid steel blocks, because under certain conditions of fastening they can bend narrowband oscillations, which translate acoustic screens at resonance frequencies from acoustically rigid to acoustically soft [6–13].

Given the latter, the most suitable material for hard acoustic screens is gray cast iron. In its structure, it has air microbubbles, like sound-reflecting rubbers or foams, which eliminates the possibility of bending resonant oscillations.

Cylindrical piezoceramic hydroacoustic transducers with an acoustic screen in the form of an open annular layer of acoustically soft material have found considerable application in the creation of modern hydroacoustic antennas. Extensive studies of the acoustic properties of such shielded radiators were presented in [7, 14, 15]. There are almost no publications on cylindrical piezoceramic transducers with a rigid acoustic screen [16]. In this regard, there is a need to study the acoustic properties of such transducers, based on the possibilities of their use in the creation of deep-water hydroacoustic VDA.

The aim of the work is to create a design support and determine on its basis the acoustic properties of cylindrical piezoceramic radiators, shielded by an open annular layer of rigid material.

PROBLEM STATEMENT AND ITS SOLUTION

Consider the problem of sound radiation by a cylindrical piezoceramic hydroacoustic transducer, a partially shielded acoustic screen of the rigid type (Fig. 1a).

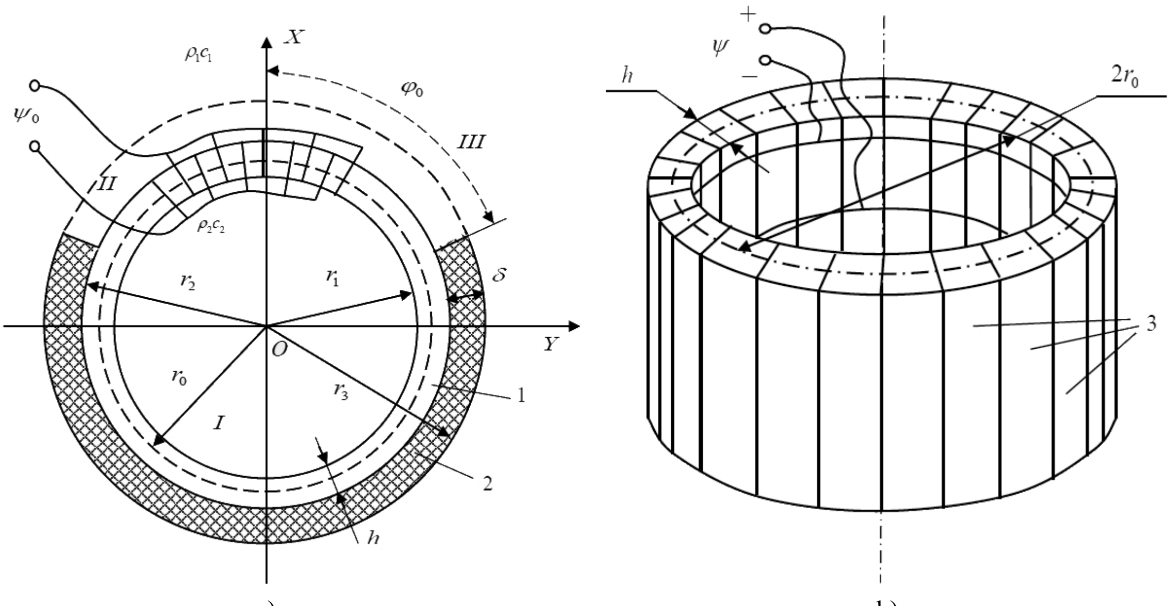

Fig. 1. Normal section (a) and scheme of construction of a segmented piezoceramic shell shielded converter (b)

The transducer consists of a cylindrical piezoceramic shell 1 (Fig. 1a) with circular polarization and an acoustic screen. Piezoceramic shell 1 with an average radius r_0 and thickness h is formed from N rigidly glued together prisms 3, electrically connected in parallel. A harmonic voltage $\psi = \psi_O e^{-i\omega t}$ of amplitude ψ_0 and circular frequency ω is applied to the prisms. Acoustic screen thickness $r_3 - r_2$ (Fig. 1a) is made of acoustically rigid material in the form of an open annular layer with an opening angle $2\varphi_0$. The transducer is placed in an elastic medium with density ρ_2 and speed of sound c_2. The inner cavity of its piezoceramic shell 1 is filled with an elastic medium with density ρ_1 and speed of sound c_2 or can be vacuumed.

The physical processes involved in the radiation of sound by such transducers are the conversion of electrical energy into mechanical energy and then into electrical energy and into the formation of the latter in the environment. When energy is converted, electric, mechanical and acoustic fields interact with each other. In the formation of acoustic energy, the piezoceramic shell and the screen create their own acoustic fields, which interact with each other due to repeated reflection of sound waves radiated by the piezoceramic shell and reflected by the acoustic screen in the external environment and the inner surface of the piezoceramic shell. The processes of energy conversion and its formation are also interconnected because they include the same acoustic field.

Based on the above physical model of the shielded converter, we develop its calculation model (Fig. 1a). Place the transducer in the Cartesian system $O\ XYZ$ (as shown in Fig. 1a) and connect the cylindrical coordinates (r, φ). The area of existence of the acoustic field of the shielded radiator is divided into three partial areas:

- the first internal coordinates:

$$0 \le r \le r_1 = r_0 \frac{h}{2};\ \ 0 \le |\varphi| \le \pi;$$

- the second intermediate coordinates:

$$r_2 \le r \le r_3 = r_2 + \delta;\ \ r \ge r_3;\ \ 0 \le |\varphi| \le \pi;$$

- the third external, defined within: $r \ge r_3$; $0 \le |\varphi| \le \pi$.

Assume that all working environments in these areas are described by a model of an ideal acoustic environment.

In mathematical terms, considering all these physical features that accompany the process of sound radiation by a shielded radiator consist in joint solution of a differential equations system that describe three fields — acoustic, mechanical and electrical.

The acoustic field for the harmonic process is described by the Helmholtz equation, which describes the motion of the media inside and outside the radiator:

$$\Delta\,\Phi + k_i\,\Phi = 0, \qquad (1)$$

where Δ– is the Laplace operator; Φ – potential of oscillating speed; $k_i = \frac{2\pi}{\lambda}$ – wave number ($i = 1,2,3$ – respectively internal, intermediate and external environment).

The mechanical field is described by the differential equations of electromechanical oscillations of cylindrical piezoceramic shells in vacuum in cylindrical coordinates. Considering the equations of piezoceramics state for circumferential polarization, the Cauchy ratio and the equations of motion of a piezoceramic element, these equations take the form [8]:

$$\begin{aligned} &(1+\beta)\frac{\partial^2 u}{\partial\varphi} + \frac{\partial w}{\partial\varphi} - \beta\frac{\partial^3 w}{\partial\varphi} = a_S\gamma_S\frac{\partial^2 u}{\partial t^2}, \\ &-\frac{\partial u}{\partial\varphi} + \beta\left(\frac{\partial^3 w}{\partial\varphi^3} - \frac{\partial^4 w}{\partial\varphi^4}\right) - w + \frac{e_{33}r_0}{C_{33}^E}E_\varphi + \frac{a}{h}q_r = a\gamma\frac{\partial^2 w}{\partial t^2}, \end{aligned} \qquad (2)$$

where u and w – are the tangential and radial components of the vector of displacements of the points of the middle surface of the shell; $\beta = \frac{h^2}{12r_0^2}\left(1+\frac{e_{33}^2}{C_{33}^E\varepsilon_{33}^S}\right)$; $a = \frac{r_0^2}{C_{33}^E}$;

q_r– external load on the shell; γ – density of piezoceramics;

e_{33}, C_{33}^E, ε_{33}^S, – respectively piezoconstant, modulus of elasticity at zero electric voltage, dielectric constant at zero deformation.

The electric field corresponds to the equations of forced electrostatics for piezoceramics:

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

where $\vec{E}$ and $\vec{D}$ – vectors of electric field strength and induction.

Since the cross-sectional dimensions of the radiator can be close or commensurate with the size of the working wavelengths of the radiator, as methods for solving equations (1)–(3) you can choose the method of distribution of variables and the method of partial domains. The choice of partial area boundaries was given above.

Relationships (1)–(3) are not a mathematical model of the specific situation under consideration. This concretization is achieved by specifying several factors: the shape of the boundaries of the fields of existence of fields, the physical conditions of these boundaries, the nature of their movement and the distribution of sound sources, etc. [5]. Execution of the function of concretization of the mathematical model is entrusted to the boundary conditions. These conditions are divided into kinematic and dynamic conditions of conjugation of fields.

Kinematic conditions of conjugation of fields include boundary conditions on the surface of the screen and the equality of the normal components of the vibrational velocities of the shell and the medium or two media on the surfaces of their contacts and have the form:

– on the inner walls of the screen

$$\frac{\partial \Phi}{\partial \varphi} = 0, \quad |\varphi| = \varphi_0, \quad r_2 \le r \le r_3; \tag{4}$$

– on the outer surface of the screen

$$-\frac{\partial \Phi}{\partial \varphi} = 0, \quad \varphi_0 \le |\varphi| \le \pi, \quad r = r_3; \tag{5}$$

$$-\frac{\partial \Phi_1}{\partial r} = \frac{\partial w}{\partial t}, \quad 0 \le |\varphi| \le \pi, \quad r = r_1; \tag{6}$$

$$-\frac{\partial \Phi_2}{\partial r} = \frac{\partial w}{\partial t}, \quad |\varphi| \le \varphi_0, \quad r = r_2; \tag{7}$$

$$-\frac{\partial \Phi_3}{\partial r} = \begin{cases} \frac{\partial \Phi_2}{\partial r}, |\varphi| \le \varphi_0, r = r_3; \\ 0, \varphi_0 \le |\varphi|. \end{cases} \tag{8}$$

The dynamic conjugation conditions reflect the equality of the normal component of the stress tensor in the mechanical field of the piezoceramic material to the acoustic pressure in the acoustic field on the surface of the shell at the points of contact, taken with the inverse sign:

$$q_r = -(p_{II} - p_I), \quad |\varphi| \le \varphi_0, \quad r = r_1; \tag{9}$$

where $p_{II} = \rho_2 \frac{\partial \Phi_2}{\partial t}$; $p_I = \rho_1 \frac{\partial \Phi_1}{\partial t}$; – radial displacements from dynamic pressure in areas *II* and *I*.

$$\Phi_3 = \Phi_2, \quad |\varphi| \le \varphi_0, \quad r = r_3. \tag{10}$$

Electrical conditions are reduced to the voltage setting E_φ electric field in the shell material. With circumferential polarization, this condition takes the form:

$$E_\varphi = -\frac{\psi_0 M}{2\pi r_0}. \tag{11}$$

To solve the formulated problem of "through" sound radiation, we present mechanical and acoustic fields in different partial regions as follows.

The required values *u* and *w* of the mechanical field are described by expansions in rows by the eigenforms of the oscillations of the shell in vacuum:

$$u = \sum_{n=1}^{N} u_n \sin n\varphi; \quad w = \sum_{n=0}^{N} w_n \cos n\varphi. \tag{12}$$

The acoustic field generated by the transducer can be represented by the velocity potential in each of the following areas:

– in area I, which has no features in the internal volume of the converter

$$\Phi_1 = \sum_{m=1}^{\infty} E_m J_m(k_1 r)\cos(m\varphi); \tag{13}$$

– in area II

$$\Phi_2 = \sum_{q=0}^{\infty}\left[A_q J_{mq}(k_2 r) + B_q N_{mq}(k_2 r)\right]\cos(m_q\varphi); \tag{14}$$

– in area III, taking into account the radiation at infinity

$$\Phi_3 = \sum_{S=0}^{\infty} F_S H_S^{(1)}(k_2 r)\cos(S\varphi); \tag{15}$$

where $J_n(kr)$, $N_{mq}(kr)$, $H_S^{(1)}(kr)$ – Bessel functions, Neumann Hankel of radial first kind, E_m, A_q, B_q, F_S – unknown complex coefficients of schedules.

The expression for the velocity potential Φ_I satisfies the Helmholtz equation for arbitrary ones m_q. Proper selection of this value can achieve the satisfaction of the boundary conditions in area *II*. To do this, substitute expression (14) in the boundary condition (4):

$$\frac{\partial \Phi_2}{\partial \varphi} = -m_q \sum_{q=0}^{\infty}\left[A_q J_{mq}(k_2 r) + B_q N_{mq}(k_2 r)\right]\sin(m_q\varphi_0), \rightarrow \sin(m_q\varphi_0) = 0;$$

$$m_q\varphi_0 = \pi q; \rightarrow m_q = \frac{\pi q}{\varphi_0}.$$

The coefficients u_n and w_n decompositions (12) should be determined on the basis of satisfying equation (2) and conjugation conditions (7), (9). From the first equation of the system follows the following relationship between the required coefficients:

$$u_n = \frac{n(1+\beta n^2)}{\alpha\gamma\omega^2 - (1+\beta)n^2} w_n. \tag{16}$$

Substituting (14) into the second equation of system (2) and carrying out its transformation, we obtain:

$$\sum_{n=0}^{\infty} R_n w_n \cos(n\varphi) -$$

$$-i\omega\frac{\alpha}{h}\left(\rho_2\sum_{q=0}^{\infty}\left[A_q J_{mq}(k_2 r)+B_q N_{mq}(k_2 r_2)\right]\cos(m_q\varphi)-\rho_1\sum_{m=0}^{\infty}E_m J_m(k_1 r_1)\cos(m\varphi)\right)=$$

$$=-\frac{e_{33}\psi_0}{C_{33}^E 2\pi},$$

where $R_n=\dfrac{\alpha^2\gamma^2\omega^2-\alpha\gamma\omega^2\left(1+\beta n^2\right)\left(n^2+1\right)+\beta n^2\left(n^2+1\right)^2}{\alpha\gamma\omega^2\tau^2-(1+\beta)n^2}$.

A number of algebraic equations follow:

- from conditions (4) and (6):

$$\sum_{m=0}^{\infty}E_m J'_m(k_1 r_1)\cos(m\varphi)=ic_1\sum_{n=0}^{\infty}w_n\cos(n\varphi),\quad 0\le|\varphi|\le\pi.$$

- from conditions (4) and (7):

$$\sum_{q=0}^{\infty}\left[A_q J'_{mq}(k_2 r_2)+B_q N'_{mq}(k_2 r_2)\right]\cos(m_q\varphi)=ic_2\sum_{n=0}^{\infty}w_n\cos(n\varphi), \quad (17)$$

- condition (4) and (8) gives:

$$\sum_{S=0}^{\infty}F_S H_S'^{(1)}(k_2 r_3)\cos(S\varphi)=\sum_{q=0}^{\infty}\left[A_q J'_{mq}(k_2 r_2)+B_q N'_{mq}(k_2 r_2)\right]\cos(m_q\varphi),$$

$$|\varphi|\le\varphi_0.$$

Algebraization of equations system (17) based on the properties of completeness and orthogonality of angular functions on the intervals $[-\pi, \pi]$, $[-\varphi_0, \varphi_0]$ and $[\varphi_0, 2\pi-\varphi_0]$, respectively leads to the following infinite system of linear algebraic equations:

$$\begin{cases} w_n\left(R_n+\dfrac{\alpha\omega\rho_1 c_1}{h}\dfrac{J_n(k_1 r_1)}{J'_n(k_1 r_1)}\right)N_n-\dfrac{\alpha\omega\rho_2}{h}\displaystyle\sum_{q=0}^{\infty}\left[A_q J_{mq}(k_2 r_2)+B_q N_{mq}(k_2 r_2)\right]N_{nq}=-\dfrac{e_{33}\psi_0 M}{C_{33}^E 2\pi}b_n,\ n=0,1,\ldots; \\ \displaystyle\sum_{q=0}^{\infty}\left[A_q J'_{mq}(k_2 r_2)+B_q N'_{mq}(k_2 r_2)\right]N_q-ic_2\sum_{n=0}^{\infty}w_n N_{nq},\ q=0,1,\ldots; \\ \left[A_q J'_{mq}(k_2 r_3)+B_q N'_{mq}(k_2 r_3)\right]N_q-\displaystyle\sum_{S=0}^{\infty}F_S H_S'^{(1)}(k_2 r_3)N_{qS}=0,\ q=0,1,\ldots. \end{cases} \quad (18)$$

The coefficients of the system (18) are:

$$N_n=\begin{cases}2\pi,\ n=0;\\ \pi,\ n\ne 0.\end{cases}$$

$$N_{nq}=\begin{cases}\varphi_0,\ n=m_q;\\ \dfrac{2m_q(-1)^{q+1}\cos(n\varphi_0)}{n^2-m_q^2},\ n\ne m_q.\end{cases}$$

$$N_q=\begin{cases}2\varphi_0,\ m_q=0;\\ \varphi_0,\ m_q\ne 0.\end{cases}$$

$$N_S=\begin{cases}2\pi,\ S=0;\\ \pi,\ S\ne 0.\end{cases}$$

$$N_{Sq}=\begin{cases}\varphi_0,\ S=m_q;\\ \dfrac{2m_q(-1)^{q+1}\cos(S\varphi_0)}{S^2-m_q^2},\ S\ne m_q.\end{cases}$$

$$b_n=\int_0^{\pi}\cos(n\varphi)\,d\varphi.$$

After regularization of the infinite system (18) by known methods [6–8] it can be solved by the method of reduction or by the method of successive approximations.

We use the obtained relations to quantify the directional properties of a cylindrical piezoceramic hydroacoustic radiator, partially shielded by a rigid acoustic screen. Define its $D(\varphi)$ diagram according to the expression:

$$D(\varphi)=\frac{\sum_{n=0}^{L}F_n e^{-i\frac{n\pi}{2}}\cos(n\varphi)}{\max\sum_{n=0}^{L}F_n e^{-i\frac{n\pi}{2}}\cos(n\varphi)}, \quad (19)$$

where L – is the reduction factor of an infinite system (18).

Calculations of the radiation diagrams of the shielded radiator are performed according to expressions (18) and (19) for wide changes in its parameters. The following parameters are accepted as the last. The radiators are formed from piezoceramics of composition CTBS-3 in the form of partitioned structures with the number of prisms in the structure of piezoceramic rings $M = 48$. The average radius of the piezoceramic shell is $r_0 = 0.008$ m. The excitation voltage was assumed to be equal $\psi_0 = 50$ *V*. The acoustically rigid screen is made in the form of an open annular sector with a thickness $r_3 - r_2$ with opening angles $\varphi_0 = 30°$, $90°$, $150°$. The thickness of the annular layer was 0.008 m. The frequency range of the study was 200 – 12000*Hz*. The value of the shear level of an infinite system of linear algebraic equations (18) was chosen based on the conjugation of boundary conditions (6)–(10) with an accuracy of 5 %. The number of considered members in relations (18) and (19) was 30. The most typical results of calculations of the angular dependence of normalized amplitudes of acoustic pressure in the far zone of the system are given in Fig. 2 – 4.

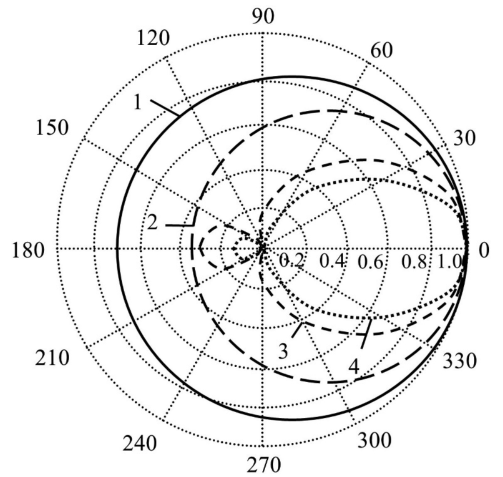

Fig. 2. Directional diagrams of the shielded radiator with $\varphi_0 = 30°$ with frequency: f =200 Hz (curve 1); 1000 Hz (curve 2); 5000 Hz (curve 3); 10000 Hz (curve 4)

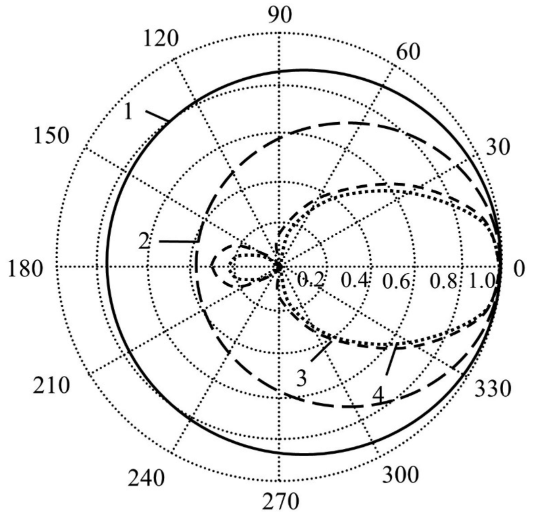

Fig. 3. Directional diagrams of the shielded radiator with φ_0= 90° with frequency: f =200 Hz (curve 1);
1000 Hz (curve 2); 5000 Hz (curve 3); 10000 Hz (curve 4)

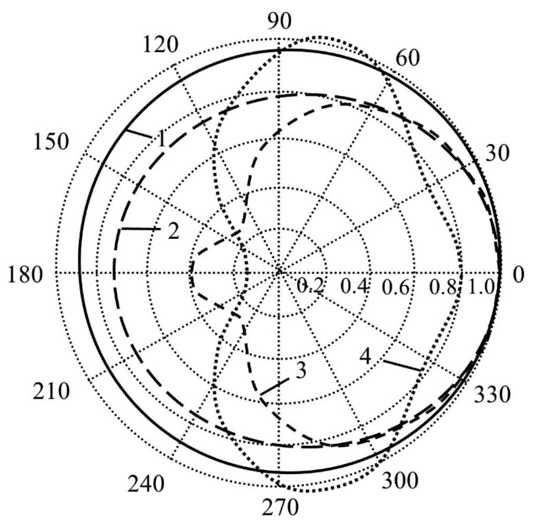

Fig. 4. Directional diagrams of the shielded radiator with φ_0= 150° with frequency: f =200 Hz (curve 1);
1000 Hz (curve 2); 5000 Hz (curve 3); 10000 Hz (curve 4)

The analysis of calculations results testifies to the following.

In the region of low operating frequency $f < 500$ *Hz* (curve 1), the radiation of sound by the shielded radiator in its cross section is almost uniform (of the order of 0.8 from the maximum level) for all angular directions and remains almost unchanged at all angles φ_0 of the hard screen. This indicates that the shielding effect of the rigid acoustic screen, even at large angles (Fig. 2), the shielding of the cylindrical radiator is almost absent.

The transition to the mid-frequency range $f \sim 1000$ Hz (curve 2) is accompanied by the appearance of not significant, but one-way directional properties. The level of radiation on the screen side is reduced compared to the level of radiation in the center of the radiation angle $2\varphi_0$. In this case, the smaller the shielded angle (360°– $2\varphi_0$), the lower the level of unilateral orientation of the shielded radiator. If at $2\varphi_0$ =60° this level is 0.5 of the maximum value of radiation, then at $2\varphi_0$ =300° it rises to values of 0.7 from the maximum level.

A further increase in the operating frequency of the shielded radiator turns it into an radiator with significant unilateral radiation (Fig. 4, curves 3, 4). The level of the rear petal of the radiation diagram of the radiator is significantly reduced and reaches values of 0.05 from the maximum radiation. Its smallest values occur at the shielding angle $2\varphi_0$ =180° (Fig. 3). Changing the shielding angle 360°– $2\varphi_0$ causes the appearance of the rear petal of the diagram, which "breathes" within (0,05÷0,3) of the maximum value when changing the frequency of radiation. Another feature of high operating frequencies of radiation is the dependence of the width $\Delta\varphi$ of the radiation diagram of the shielded radiator on the value of the operating frequency. At the angle of opening of the screen which is in the range from 30° to 100°, increase in working frequency is followed by decrease $\Delta\varphi$.

The main petal of the radiation diagram of the shielded radiator is almost close to the shape of a unidirectional $\cos\varphi$. With a further increase of the angle φ_0 of opening of the screen (Fig. 4, curves 3, 4), the main petal of the diagram begins to expand, taking the form of cardioids $\frac{1+\cos\varphi}{2}$. Moreover, a further increase of frequency (Fig. 4, curve 4) lays to change the cardioid, reducing the level of the radiation pattern of such a radiator along the axis of the opening angle of the screen and close to it.

CONCLUSIONS

It is shown that in hydroacoustic stations with deep-water antennas of variable depth, it is most expedient to use acoustic screens of rigid type. The "through" problem of sound radiation by a cylindrical piezoceramic hydroacoustic transducer shielded by a rigid acoustic screen in the form of an open annular layer of finite thickness is solved by the method of connected fields in multiconnected domains. This takes into account the connection of electric, mechanical and acoustic fields in energy conversion, the connection of acoustic fields of the piezoceramic shell and the screen in the formation of acoustic fields of the radiator with the screen and the interaction of conversion and energy formation. The compatible solution of a differential equations system describing physical fields of different nature is reduced to the solution of an infinite system of linear algebraic equations with respect to the unknown decomposition coefficients of the required physical fields into Fourier series. Quantitative calculations of the directional properties of the acoustic fields of shielded radiators depending on the frequency of sound radiation and the opening angle of the hard screen are performed and their physical analysis is performed.

The results of the research can be used in the development and operation of sonar stations with deep-sea antennas of variable depth.

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АКУСТИЧНІ ВЛАСТИВОСТІ ГЛИБОКОВОДНОГО ЕКРАНОВАНОГО ГІДРОАКУСТИЧНОГО ВИПРОМІНЮВАЧА

Обґрунтована необхідність застосування в гідроакустичних станціях з глибоководними антенами змінної глибини акустичних екранів жорсткого типу. Методом зв'язаних полів в багатозв'язних областях для антен, утворених із циліндричних п'єзокерамічних випромінювачів з жорсткими екранами у вигляді незамкнутих кілець кінцевої товщини одержані аналітичні вирази для розрахунків акустичних полів таких випромінювачів. При розв'язку задачі «наскрізного» випромінювання екранованим випромінювачем враховані взаємодії: електричних, механічних і акустичних полів при перетворенні енергії; акустичних полів оболонки і екрану при формуванні енергії; процесів перетворення і формування енергії. Наведені кількісні результати розрахунків акустичних полів за одержаними виразами. Виконано аналіз акустичних властивостей випромінювачів, екранованих жорстким екраном.

Показано, що в гідроакустичних станціях з глибоководними антенами змінної глибини найбільш доцільним *є застосування акустичних екранів жорсткого типу. Методом зв'язаних полів в багатозв'язних областях розв'язана «наскрізна» задача випромінювання звуку циліндричними п'єзокерамічним гідроакустичним перетворювачем, екранованим акустичним екраном жорсткого типу у вигляді незамкнутого кільцевого шару конечної товщини. При цьому враховані зв'язок електричного, механічного і акустичного полів при перетворенні енергії, зв'язок акустичних полів п'єзокерамічної оболонки і екрану при формуванні акустичних полів випромінювача з екраном і взаємодія процесів перетворення і формування енергії між собою. Виконані кількісні розрахунки направлених властивостей акустичних полів екранованих випромінювачів в залежності від частоти випромінювання звуку та кута розкриву жорсткого екрану і проведено їх фізичний аналіз.*

Результати виконаних досліджень можуть бути використані при розробці та експлуатації гідроакустичних станцій з глибоководними антенами змінної глибини.

Ключові слова: *циліндричний п'єзокерамічний випромінювач, жорсткий екран, акустичне поле.*

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Стаття надійшла до редколегії 06.05.2021.