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ENERGY CHARACTERISTICS OF MULTIFUNCTIONAL HYDROACOUSTIC COMPLEXES WITH ELECTROELASTIC ACOUSTIC SCREENS

It is shown that one of the approaches to ensuring the multi-functionality of ship hydroacoustic instruments is the transition from several hydroacoustic stations to one multifunctional hydroacoustic complex. For this purpose, it is proposed to replace passive acoustic screens with active electroelastic bodies in these devices, the acoustic properties of which can be quickly controlled with the help of electric voltage. Analytical relations for determining the radiated acoustic energy were obtained for a typical element of hydroacoustic complex, which consists of an electroelastic transducer and an acoustic screen, under the conditions of connectedness of physical fields and processes by the method of connected fields in multi-connected regions. Numerical dependencies of radiated acoustic energy for different spatial directions of radiation and different options for excitation of an active acoustic screen were established by the method of numerical experiment and analysis of its results. Energy results are compared for a typical element and its single transducer.

Key words: *electroelastic acoustic screen, transducer, energy characteristics, electrical excitation of the screen.*

INTRODUCTION

To fulfill their combat tasks, ships of the Navy have recently been equipped with many hydroacoustic stations (HAS) of various purposes [1, 2], their main purpose is to illuminate the underwater situation, including:

– detection of targets at the greatest possible distances;
– classification of targets at medium distances using active and passive modes of HAS operation and high-precision processing of detected signals;
– localization of targets at short distances in active and passive modes with determination of current coordinates and parameters of target movement.

In addition, HAS provide underwater sound communication between ships, their mutual recognition, technical intelligence in the form of detection of hydroacoustic radiation and countermeasures against enemy hydroacoustic instruments. And there are also actual tasks related to the self-defense of the ship. These include anti-torpedo protection, protection against combat swimmers – saboteurs. Preservation of the combat stability of the ship is achieved by the ship's hydroacoustic instruments of illumination of the immediate situation – detection of mines, navigational obstacles and avoidance of them.

An obligatory element of any HAS is its hydroacoustic antenna. Its placement on the ship needs to meet a number of requirements. First, in the underwater part of the ship's hull, transport compartments must be allocated for placing hydroacoustic antennas in them. Secondly, these compartments should be located in that part of the ship's hull, where comfortable acoustic conditions are fully created for the further operation of hydroacoustic antennas. In most cases, they occupy the front third of the ship.

But in modern hydroacoustics, the tendency to reduce the operating frequencies of HAS is gaining ground, due to the need to increase the detection range of underwater objects. Its practical implementation is related to the increase in the size of the hydroacoustic antennas of the HAS in order to preserve the directional properties of the HAS. In turn, this requires an increase in the size of transport compartments for placing hydroacoustic antennas in the hull of ships, which is impossible for most classes of modern ships.

In order to solve this problem, several approaches have been proposed. The first of them was related to the removal of overall low-frequency hydroacoustic antennas outside the ship's hull [1–4]. This is how HAS with variable depth antennas appeared. These include HAS with lowering and HAS with towed hydroacoustic antennas. A feature of these HAS is the possibilities associated not only with the increase in the size of their hydroacoustic antennas, but also with their placement at depths associated with optimal hydrological conditions for the propagation of sound waves in marine environments [1, 2]. Naturally, the transition to HAS with variable depth antennas led to the creation of new types of hydroacoustic antennas: concentrated, structurally compatible with distributed reception and radiation functions [3], concentrated based on multimode transducers [5], flexible extended towed [2] and others [4].

The second approach is related to the replacement of several single-function HAS with hydroacoustic antennas placed in the ship's hull with one multifunctional hydroacoustic complex (HAC) [6].

At the same time, the main modes of operation of the HAC are the modes of echo direction finding and noise direction finding. Additional modes include underwater sound communication, detection of hydroacoustic signals, anti-torpedo protection, and countermeasures against the enemy's hydroacoustic instruments. All these modes are based on the use of a wide range of frequencies, including low frequencies. Their technical implementation can be carried out on one hydroacoustic antenna, provided that its acoustic properties change dynamically depending on the need, thus eliminating the need to place many hydroacoustic antennas in the ship's hull. This simplifies the conditions for ensuring the acoustic comfort of the operation of this antenna on the ship. Usually, the creation of spatial selectivity of hydroacoustic devices is carried out by introducing acoustic screens into their hydroacoustic antennas [1, 2]. Until recently, these were passive acoustic screens – acoustically soft, acoustically hard or impedance [3, 4, 7]. Their acoustic properties can be changed only by changing the screen type. At the same time, the latter can be achieved by using active acoustic screens during the construction of antennas. These include acoustic screens based on electroelastic bodies. Such screens have an electrical side, thanks to which changing the amplitude and phase of the electric excitation of the electroelastic body creates the possibility of operational control of both the acoustic properties of the screen and, accordingly, the frequency characteristics and spatial selectivity of hydroacoustic antennas and complexes.

As is known [3, 5, 6], a feature of performance of hydroacoustic antennas as electroelastic devices of the functions of energy transformation and formation is the connection of physical fields and the above functions with each other during the operation of the antennas.

For the practical application of HAC with acoustic screens based on electroelastic bodies, it is necessary to investigate, firstly, the scientific principles of determining the active physical fields and processes in the conditions of connectivity and, secondly, the quantitative regularities of their dependence on the parameters and characteristics of electroelastic screens in various conditions operative management of them.

Therefore, the purpose of this work is to study the energy characteristics of hydroacoustic antennas with electroelastic screens in the conditions of connectivity and operational control of screen parameters.

STATEMENT AND SOLUTION OF THE PROBLEM

First of all, let's note that in most cases, shipboard HAS and HAC are built on the basis of circular cylindrical hydroacoustic antennas [1-6]. Their positive quality is that they can work in the modes of circular and sector radiation and reception of sound energy. A typical element of such antennas is an electroelastic transducer placed next to the acoustic screen. Knowing its frequency, energy and spatial dependences, it is possible to further determine all the necessary characteristics of circular antennas in different modes of their operation.

Consider a typical element, the physical model of which is shown in Fig. 1 a. The element consists of a circular cylindrical electroelastic screen 1 and an electroelastic transducer 2 with parallel longitudinal axes. Acoustic screen 1 has an average radius r_{01}, thickness d_1 and is made in the form of a segmented body with M_1 piezoceramic segments – a prism. Transducer 2 with average radius r_{02}, thickness d_2 is also made of M_2 piezoceramic prisms and is located at a distance l from screen 1. The prisms are rigidly connected to each other and electrically connected in parallel. Compositions of piezoceramics of the screen and the transducer can be the same or different. This approach with the same or different average radii r_{01} and r_{02} allows to study the characteristics of a typical element with the same or different main resonance frequencies of its components.

The internal cavities of the screen and transducer structures can be vacuumed, filled with HAS or liquid. The electric excitation of the electroelastic screen and the transducer is carried out by electric voltages ψ_1 and ψ_2, respectively, the phase shift between which is the value of φ.

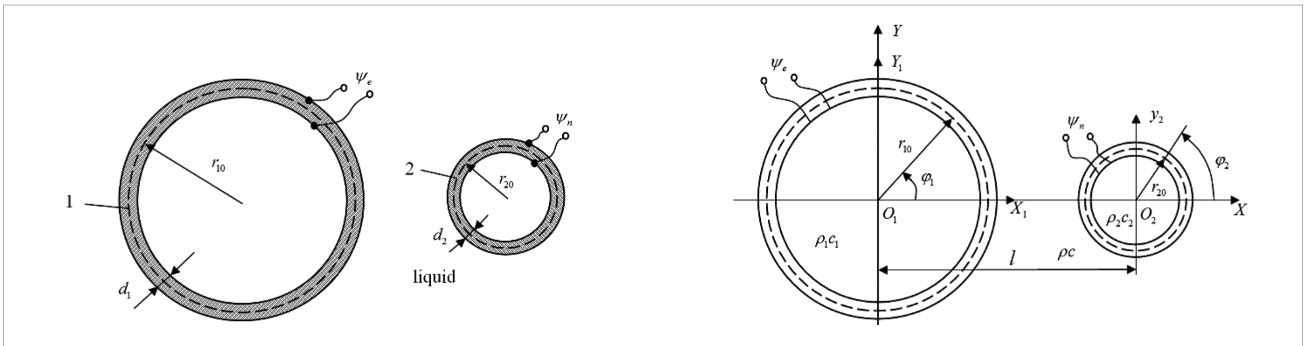
The calculation model (Fig. 1 b) of a typical element is formed from its physical model by placing it in the general Cartesian coordinate system $OXYZ$, and each of its components in local Cartesian coordinates ($0_s x_s y_s z_s$) and related to them circular cylindrical (r_s, φ_s, z_s) coordinates (s=1, 2). A typical element surrounds the environment i=1 with specific wave resistance $\rho_1 s_1$, where ρ_1 and s_1 are the density and propagation speed of sound waves in it, respectively. The internal cavities of the screen and transducer are filled with media i=2 with wave resistances $\rho_{2s} c_{2s}$, where s=1 for the screen and s=2 for the transducer.

In mathematical terms, the consideration of connectivity conditions can be taken into account [1−3] by jointly solving a system of three differential equations:

– the Helmholtz wave equation, which characterizes the movement of media in all partial i=1, 2 regions:

$$\Delta\Phi_{is} + k_{is}\Phi_{is} = 0,\ s=1,\ 2;\ i=1,\ 2;$$

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



a) *b)*

F i g . 1. Physical model (*a*) and calculation model (*b*) of a typical antenna element

$$\left(1+\beta_s\right)\frac{\partial^2 u_s}{\partial\varphi_s^2}+\frac{\partial w_s}{\partial\varphi_s}-\beta_s\frac{\partial^2 w_s}{\partial\varphi_s^2}=\alpha_s\gamma_s\frac{\partial^2 u_s}{\partial t^2};$$

$$-\frac{\partial u_s}{\partial\varphi_s}+\beta_s\left(\frac{\partial^2 u_s}{\partial\varphi_s^2}-\frac{\partial^4 w_s}{\partial\varphi_s^4}\right)-w_s+\frac{e_{33s}}{C_{33s}^E}r_{0s}E_{\varphi s}+ \quad ;(1)$$

$$+\frac{\alpha_s}{h_s}q_{is}=\alpha_s\gamma_s\frac{\partial^2 w_s}{\partial t^2};\ s=1,\ 2$$

– equations of forced electrostatics for piezoceramics:

$$\vec{E}_s=-\,grad\psi_s;\ \vec{D}_s=0;\ s=1,\ 2.$$

Interpretations of all notations in expressions (1) are given in [9], and the intensity of electric fields is defined as $E_{\varphi s}=\psi_s M_s/2\pi r_{0s}$.

To solve the system (1) of differential equations, we apply the method of coupled fields in multi-connected regions. As partial areas, we will choose the outer (i=1) and inner (i=2) areas of the screen (s=1) and the transducer (s=2).

Then the kinematic and dynamic conditions of the conjugation of the acoustic and mechanical fields at the boundaries of the partial regions will have the form:

$$-\frac{\partial\Phi_1\left(r_s,\varphi_s\right)}{\partial r_s}=\frac{\partial w_s}{\partial t},0\le\varphi_s\le 2\pi,r_s=r_{1s}=r_{0s}+h_s/2;$$

$$-\frac{\partial\Phi_2\left(r_s,\varphi_s\right)}{\partial r_s}=\frac{\partial w_s}{\partial t},0\le\varphi_s\le 2\pi,r_s=r_{2s}=r_{0s}-h_s/2; \quad (2)$$

$$q_{rs}=\left[\frac{\rho_1\partial\Phi_1}{\partial t}-\frac{\rho_{2s}\partial\Phi_2}{\partial t}\right],0\le\varphi_s\le 2\pi,r_s=r_{0s},s=1,\ 2.$$

where Φ_1 (r_s,φ_s) and Φ_2 (r_s,φ_s) is the velocity potential of the external (i=1) and internal (i=2) acoustic fields of the screen (s=1) and the transducer (s=2).

Let's determine the mechanical and acoustic fields of the components of a typical element in the form of expansions in Fourier series by angular and wave cylindrical functions, respectively:

$$u_s=\sum_n u_{ns}e^{in\varphi_s};\ w_s=\sum_n w_{ns}e^{in\varphi_s};$$

$$\Phi_{1s}\left(r_s,\varphi_s\right)=\sum_n A_{ns}H_n^{(1)}\left(k_1 r_s\right)e^{in\varphi_s}; \quad (3)$$

$$\Phi_{2s}\left(r_s,\varphi_s\right)=\sum_n B_{ns}J_n\left(k_2 r_s\right)e^{in\varphi_s},\ s=1,\ 2.$$

Then the acoustic field of a typical element in the region i=1, $\Phi_1=\sum_{s=1}^{2}\Phi_{1s}\left(r_s,\varphi_s\right)$, defined in local coordinates of the s-th element using addition theorems for cylindrical wave functions [10], takes the form

$$\Phi_1\left(k_1 r_s,\varphi_s\right)=\sum_n A_{ns}H_n^{(1)}\left(k_1 r_s\right)e^{in\varphi_s}+$$

$$+\sum_n A_{nq}\sum_m J_m\left(k_1 r_s\right)H_{n-m}^{(1)}\left(k_1 r_{qs}\right)e^{i(n-m)\varphi_{qs}}e^{im\varphi_s}, \quad (4)$$

$$s=1,\ 2;q\ne s.$$

Here $r_{qs}=l$, φ_{qs} is the angular coordinate of the center O_q in s-th coordinate system.

Algebraization of the system of functional equations (1), (2) taking into account expressions (3), (4) and using the properties of completeness and orthogonality of systems of angular functions $e^{in\varphi}$ on intervals $[0,2\pi]$ leads to the appearance of the following infinite system of linear algebraic equations:

$$-B_m J'_n\left(k_1 r_{1s}\right)+ic_{1s}w_{ms}=0;$$

$$ic_{1s}w_{ns}-A_{ns}H_n^{(1)'}\left(k_1 r_{1s}\right)+$$

$$+\sum_m A_{nq}J'_m\left(k_1 r_{1s}\right)H_{n-m}^{(1)}\left(k_1 l\right)e^{i(n-m)\varphi_{qs}}=0; \quad (5)$$

$$R_{ns}w_{ns}+\frac{\alpha_s}{h_s}i\omega\rho_1\left[\begin{array}{l}A_{ns}H_n^{(1)}\left(k_1 r_{1s}\right)+\\ \sum_m A_{nq}J_m\left(k_1 r_{1s}\right)H_{n-m}^{(1)}\left(k_1 l\right)e^{i(n-m)\varphi_{qs}}\end{array}\right]-$$

$$-\frac{\alpha_s}{h_s}i\omega\rho_{2s}B_{ns}J_n\left(k_2 r_{2s}\right)=-\frac{e_{33s}}{C_{33s}^E}\frac{\psi_s M_s}{2\pi}\int_0^{2\pi}e^{in\varphi_s}d\varphi_s;$$

$$s=1,\ 2;q\ne s.$$

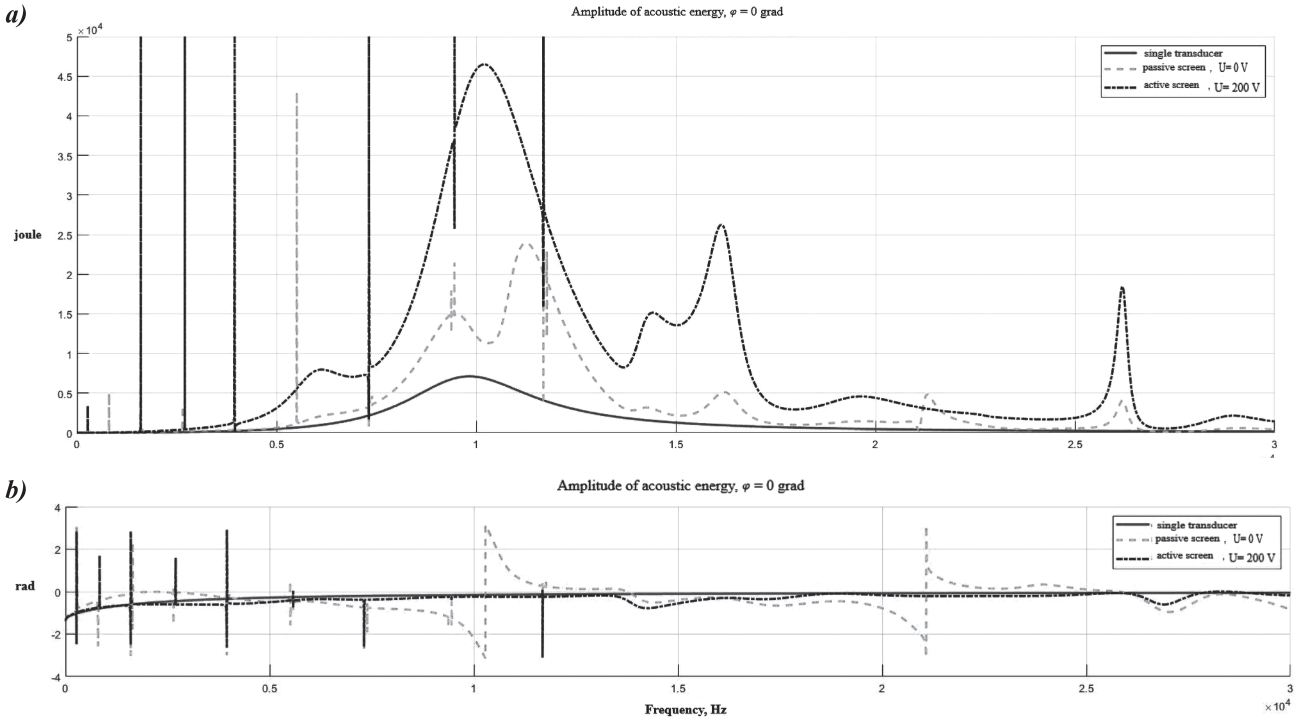
In equations (5), the expressions for R_{ns} are given in works [1, 2, 9, 10], the dash "′" means the derivative of the function. To solve the infinite system (5), the reduction method or the method of successive approximations [3, 6] is used. As a result of the solution, the quantitative values of the sought coefficients of the expansions (3) are obtained with a predetermined accuracy.

ANALYSIS AND DISCUSSION OF THE RESULTS OF THE NUMERICAL EXPERIMENT

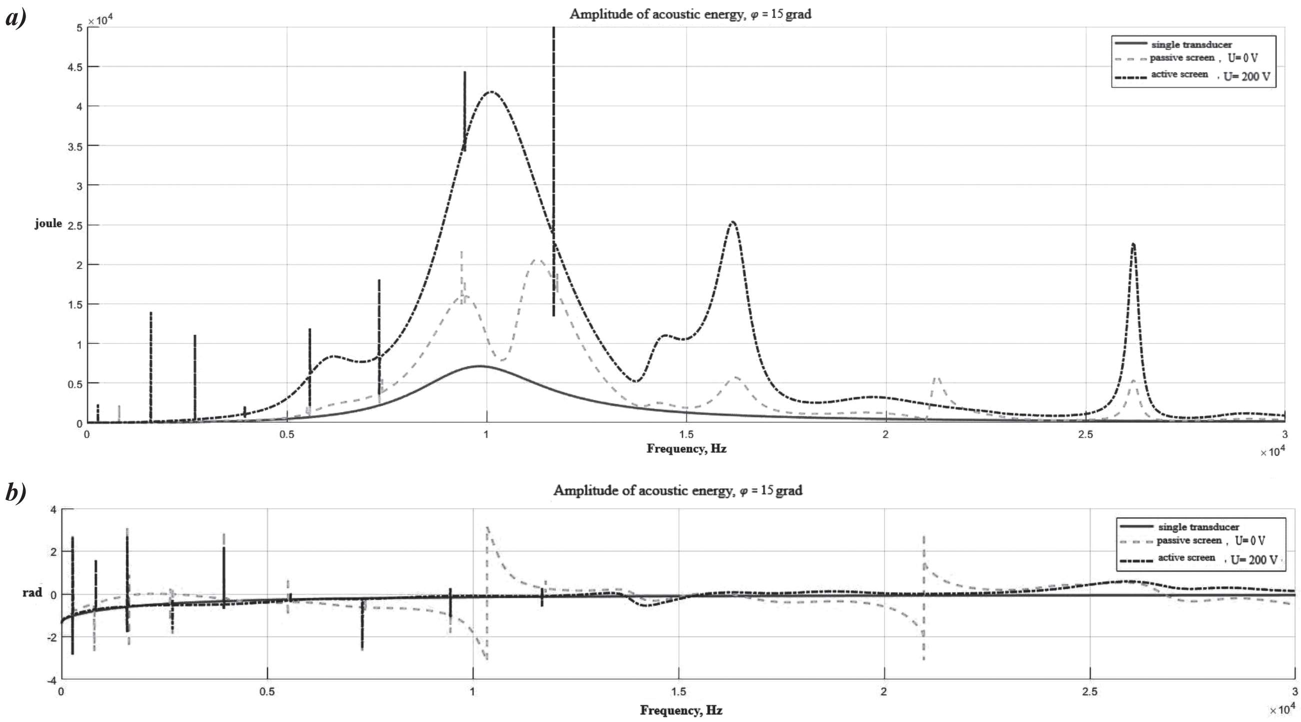
When analyzing the radiation of a typical element, the energy characteristics become important. By acoustic energy we will understand that part of the energy of the surrounding element of the environment, which is caused by the appearance of sound waves in it. For the model of an ideal compressible fluid, which is considered in the work, the total acoustic energy $E(r_s,\varphi_s)$ at any point of the medium with coordinates (r_s,φ_s) consists of kinetic and potential energies and is defined as $E(r_s,\varphi_s)=P(r_s,\varphi_s)\ \bar{W}(r_s,\varphi_s)$, where P and $\bar{W}$ respectively, are the acoustic pressure and the complex conjugate of the oscillating velocity W at the point (r_s,φ_s). In order to conduct qualitative and quantitative analyzes of sound radiation by an electroelastic transducer in the presence of an electroelastic acoustic screen under conditions of connectivity and operational control of screen parameters, calculations of the total acoustic energy of radiation of a typical element per unit length at various points around the transducer for the following element parameters were performed. The transducer and the screen are made of piezoceramics of the TSBS-3 composition with the following characteristics: density $\rho=7210$ kg/m^3; piezo constant $e_{33}=d_{33}C_{33}^E$; piezo module $d_{33}=3.8\cdot10^{10}$ C/N, dielectric constant $\varepsilon_{33}=11.328\cdot10^{-9}$ F/m, modulus of elasticity $C_{33}^E=0.75\cdot10^{-10}$ N/m^2. Both shells have the same average radius r_{01}=r_{02}=0.068 m, thickness $h_1=h_2=0.008$ m and the number of prisms $M_1=M_2=48$. The electrical excitation of the transducer was carried out with a voltage of $\psi_2=200$ V. The electroelastic screen was not excited $\psi_1=0$. Both structures were evacuated and placed in a liquid

($\rho_1 c_1$=1.5·10^6 kg/m^{2}s) at a distance between the surfaces of 0.003 m. The number of equations that were retained during the solution of the infinite system (5) was 41. At the same time, the inviscidity of the field components at the boundaries (2) partial regions did not exceed 7 %. The results of calculations of radiated energy by a typical element in different directions at points near the transducer are shown in Figs. 2–5. Curves 1 correspond to the transducer placed near the passive (excitation voltage $\psi_1 = 0$) electroelastic screen, curve 2 – near the screen excited by the voltage $\psi_1 = 200$ V, $\varphi = 0$, curve 3 – in the absence of the screen.

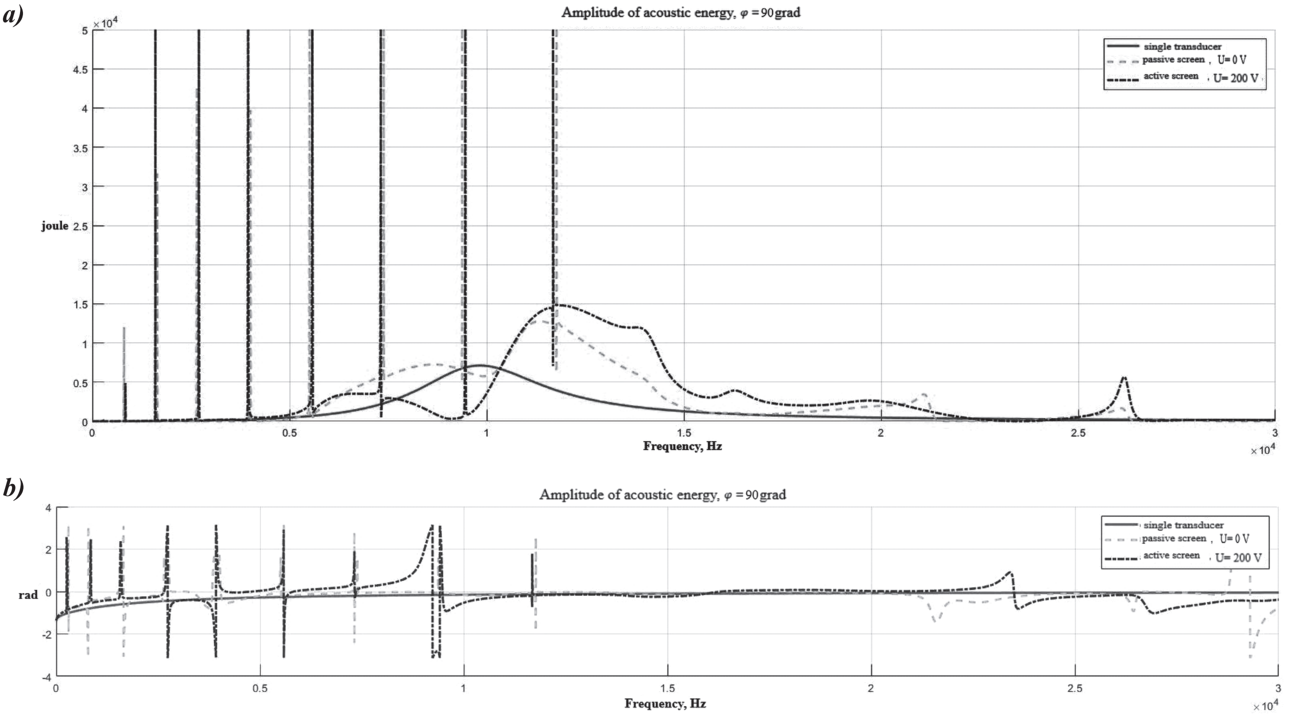
Let's analyze the obtained results. First of all, we note that in the frequency dependence of the acoustic power radiated by a typical element, two components can be distinguished – narrowband and broadband. Both are the result of the connection of physical fields and processes that occur during the transformation and formation of energy by the components of a typical element, and both undergo significant changes



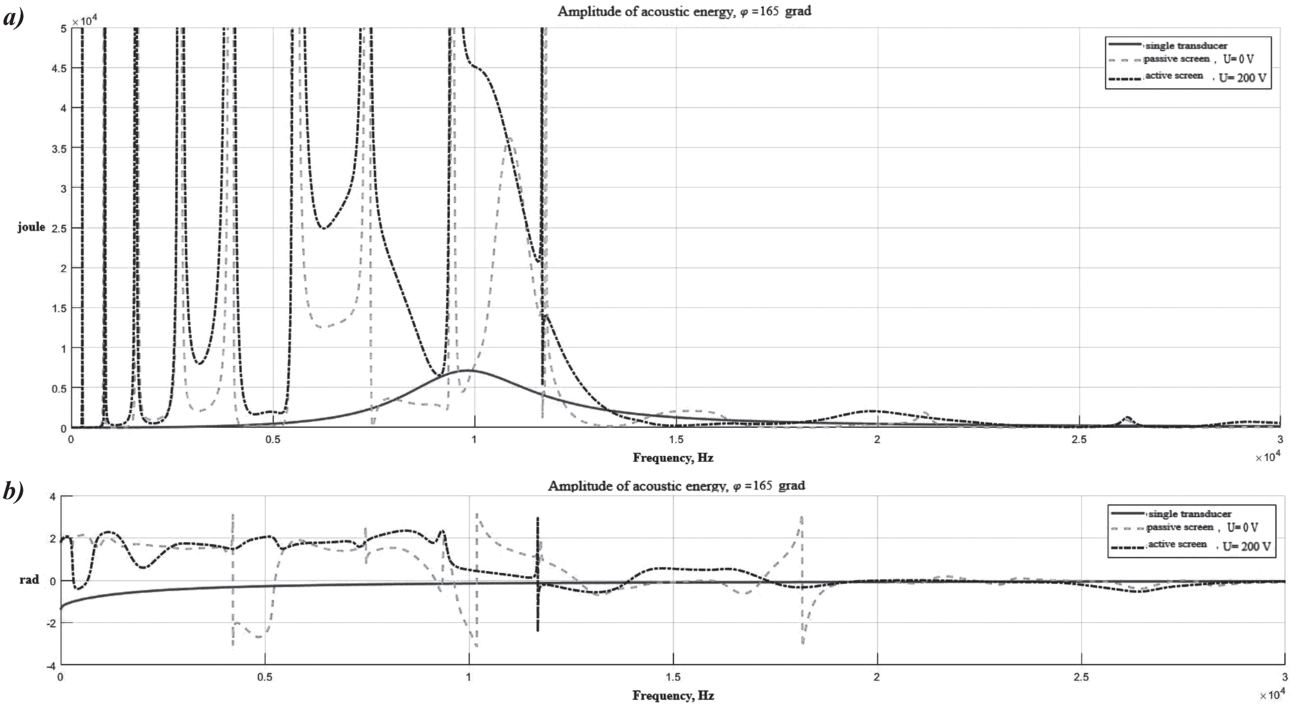
F i g . 2. Frequency dependences of the amplitude (*a*) and phase (*b*) of the radiated energy in the spatial direction $\varphi_2 = 0$



F i g . 3. Frequency dependences of the amplitude (*a*) and phase (*b*) of the radiated energy in the spatial direction $\varphi_2 = 15°$



F i g . 4. Frequency dependences of the amplitude (*a*) and phase (*b*) of the radiated energy in the spatial direction $\varphi_2 = 90°$



F i g . 5. Frequency dependences of the amplitude (*a*) and phase (*b*) of the radiated energy in the spatial direction $\varphi_2 = 165°$

depending on the position in the surrounding environment of the energy determination point. The narrowband component of acoustic power is formed by additional resonant emissions and is located in the region of low and resonant frequencies of a typical element [11]. For most points of determination of the radiated energy, their amplitudes are many orders of magnitude higher than the energy amplitude of a single transducer (without a screen) and significantly exceed the amplitudes of the energy of its broadband component. But there are certain peculiarities of the frequency behavior of the narrow-band energy component of a typical element.

First, at almost all points near the transducer, there are narrow-band energy components of a typical element coincide in frequency for cases of passive and active screens. Secondly, there are points (Fig. 3) near the transducer in which the narrow-band energy components almost disappear. Physically, this indicates that there are almost no connectivity conditions for these radiation directions. Thirdly, in those cases (Fig. 5) when the point of energy determination is located near the surface of the screen, the narrow-band energy components significantly increase their resonant bands, and moreover, their resonant frequencies begin to differ for the cases of passive and active screens. In general, the amplitudes of the radiated acoustic energy in terms of additional, narrow-band resonances at points on the side of the screen (Figs. 4, 5) significantly exceed those at points on the side of the transducer (Figs. 2, 3). Fourth, in the high-frequency region, when $(f/f_0)>1.2$, where f_0 is the resonance frequency of a single transducer, the narrow-band energy component is completely absent.

The main component of the radiated energy is a resonance curve. It is possible to distinguish three frequency regions. In the low-frequency region $(f/f_0)<0.7$ at the points on the side of the transducer (Fig. 2, 3), the radiated acoustic energy has low values, close to the values of a single transducer. This is due to the fact that at these frequencies the wave dimensions of both the transducer and the screen are small and the effects of the interaction of acoustic fields during energy formation are insignificant. At the same time, as it was established during the analysis of the frequency dependence of the narrow-band energy component in this area, the connectivity of physical fields during energy conversion plays a very significant role.

The resonant region, which extended from $(f/f_0)\in[0.7; 1.2]$ in most of the studied cases in this area, the energy radiated by a typical element in the presence of an acoustic screen excited by the voltage $\psi_1 = 200$ V significantly exceeds the same energy in the presence of a passive $(\psi_1 = 0)$ electroelastic screen. In addition, the passivity of the screen is the reason for the creation of dips in the frequency dependence of energy in the region of the resonant frequency f_0 of a single transducer. Exceptions are spatial directions in the direction $\varphi_2 = 90°$ (Fig. 4). But in all cases, the acoustic energy radiated by a typical element that has an electroelastic acoustic screen is several times higher than the energy of the transducer in the absence of an acoustic screen next to it. A feature of the resonance region is also that the resonance bands of the frequency dependences of the energy of a typical element are close to those of a single transducer.

In the third, high-frequency region, $(f/f_0)>1.2$ for most spatial directions, there are no energy emissions in the frequency dependence of the acoustic energy of a typical element. Exceptions are a number of directions (Figs. 2, 3) that are adjacent to the axis $O_1\varphi_2$ (Fig. 1) of a typical element.

CONCLUSIONS

It is shown that the task of creating multi-functionality of ship's hydroacoustic armament can be realized not only by increasing the number of hydroacoustic stations due to stations with variable depth antennas, but also by transitioning from individual hydroacoustic stations to hydroacoustic complexes. Such complexes are multifunctional and allow to provide not only such basic modes as echo direction finding and noise direction finding, but also a number of additional modes – communication, detection of hydroacoustic signals and others. The latter approach reduces the number of hydroacoustic antennas placed in the ship's hull, but for this the ship's hydroacoustic antennas must be able to control their acoustic characteristics. This possibility arises when performing acoustic screens, which in most cases are part of hydroacoustic stations, in the form of electroelastic bodies when they are excited by electric voltage.

In order to determine the possibilities of operational management of the energy characteristics of hydroacoustic stations with electroelastic screens in the conditions of the connection of active physical fields and processes, the problem of sound energy radiation by a typical element of a hydroacoustic complex consisting of an electroelastic transducer and an electroelastic acoustic screen was formulated and solved. By the method of connected fields in multi-connected regions, the compatible solution of the system of differential equations describing the functioning of a typical element is reduced to the solution of the infinite system of linear algebraic equations by the method of reduction. The dependences of the acoustic energy radiated by a typical element under connected conditions on the directions of radiation and two variants of operational excitation of the acoustic screen – in the absence of excitation and excitation with an electric voltage of 200 V were determined by means of a numerical experiment. The obtained results were compared with the energy of a single transducer without a screen.

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ЕНЕРГЕТИЧНІ ОСОБЛИВОСТІ БАГАТОФУНКЦІОНАЛЬНИХ ГІДРОАКУСТИЧНИХ КОМПЛЕКСІВ З ЕЛЕКТРОПРУЖНИМИ АКУСТИЧНИМИ ЕКРАНАМИ

Завдання створення багатофункціональності корабельного гідроакустичного озброєння може бути реалізовано не тільки шляхом збільшення кількості гідроакустичних станцій за рахунок станцій з антенами змінної глибини, але й за рахунок переходу від окремих гідроакустичних станцій до гідроакустичних комплексів. Такі комплекси є багатофункціональними і дозволяють забезпечувати на кораблі не тільки основні режими ехопеленгування та шумопеленгування, але і ряд додаткових режимів – зв`язок, виявлення гідроакустичних сигналів та ін. Останній підхід зменшує кількість гідроакустичних антен, що розміщені в корпусі корабля, але для цього корабельні гідроакустичні антени повинні мати можливість оперативного управління їх акустичними характеристиками. Така можливість виникає при виконанні акустичних екранів, які в більшості випадків входять до складу гідроакустичних станцій, у вигляді електропружних тіл при їх збудженні електричною напругою. Для типового елемента гідроакустичного комплексу, який складається із електропружних перетворювача і акустичного екрану, в умовах зв'язаності фізичних полів і процесів методом зв'язаних полів в багатозв'язаних областях з метою визначення можливостей оперативного управління енергетичними характеристиками гідроакустичних станцій з електропружними екранами сформульована і розв'язана задача випромінювання звукової енергії типовим елементом гідроакустичного комплексу у складі електропружного перетворювача і електропружного акустичного екрану. Методом зв'язаних полів у багатозв'язаних областях сумісний розв'язок системи диференційних рівнянь, що описують функціонування типового елемента, зведено до розв'язку методом редукції нескінченної системи лінійних алгебраїчних рівнянь. Шляхом чисельного експерименту визначені залежності акустичної енергії, випроміненої типовим елементом в умовах зв'язаності, від напрямків випромінювання та двох варіантів оперативного збудження акустичного екрану – при відсутності збудження і збудженні електричною напругою 200 В. Отримані результати порівняні з енергією одиночного перетворювача без екрану.

Ключові слова: *електропружний акустичний екран, перетворювач, енергетичні характеристики, електричне збудження екрану.*

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