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ANALYSIS OF POSSIBLE WAYS OF TECHNICAL IMPLEMENTATION OF POWERFUL ACOUSTIC RADIATION BY HYDROACOUSTIC STATIONS

Increasing the range of sonar stations is determined by the possibility of increasing the effective radiation of acoustic power. But these possibilities are limited by a number of physical factors related to the electric, mechanical and acoustic fields of sonar emitters. These limiting physical factors are determined and the connection of their influence on the value of radiated power of the sonar station is established. The dependence of this influence on the ways of technical realization of electric excitation of hydroacoustic emitters is shown. A qualitative analysis of the advantages and disadvantages of three fundamentally different ways of electrical excitation of emitters with increasing their radiated power is presented. The current state of the estimated support for the practical implementation of the above ways to increase the radiated capacity of sonar stations is established.

Keywords: *hydroacoustic station, acoustic power, power limiting factors, exciting voltages.*

INTRODUCTION

As is known [1, 2], the range of hydroacoustic stations (HAS) for various purposes in the echolocation mode is determined by the level of acoustic power that can be emitted by HAS. But the maximum levels of this power are limited for each HAS by a number of physical factors. These factors are related to the following. First, during the operation of the HAS in its sonar antenna, four physical fields are formed – electric, mechanical, acoustic and thermal. Secondly, in the mode of sound radiation, each HAS operates at the frequency of mechanical resonance of its sonar transducers, because at this frequency the transducers have the maximum value of the efficiency of energy conversion.

Each of these physical fields creates for the HAS its limiting factors in the mode of energy emission. In the acoustic field, the limiting factor of the magnitude of the radiated acoustic energy is the phenomenon of cavitation and the associated threshold of fluid cavitation. The phenomenon of cavitation (formation and rupture of bubbles in the liquid) mechanically destroys the radiating surfaces of the transducers and changes the specific acoustic resistance of the liquid, as cavitation bubbles act on the radiating surfaces of the transducers as an effective acoustically soft screen. This causes an increase in mechanical stresses in the structures of sonar transducers.

The presence of a mechanical field is the cause of physical factors limiting the amount of radiation. This is especially true of piezoceramic transducers, as piezoceramics are critical to tensile forces. Such efforts occur under the action of both static and dynamic loads. The first is created by hydroacoustic pressure, the second – by an electrical excitation signal. It is the last physical factor that imposes fundamental restrictions on the radiation of maximum acoustic power from the mechanical field.

For HAS, the maximum radiated power is determined by the maximum electric power that can be «pumped» into the piezoceramic transducer. The latter is limited by the allowable values of electric field strength. It is their magnitude that is the limiting physical factor in terms of the electric field.

The presence of the process of converting electrical energy into mechanical energy and mechanical energy into acoustic energy when radiating sound necessarily creates the appearance of a thermal field, which causes the heating of piezoceramic transducers. The maximum power also generates the maximum heating temperature of the transducers. This creates the risk of piezoceramics reaching the Curie point and thermal stresses. Therefore, the heating temperature is a limiting factor in the thermal field.

The purpose of this work is a qualitative and quantitative analysis of possible ways of controlled reduction of the influence of the above physical factors on the HAS radiation of maximum acoustic power.

RESEARCH RESULTS

Hydroacoustic antennas usually perform two functions – the function of energy conversion and the function of forming acoustic energy in elastic environments. In turn, each of these functions has its own characteristics [3, 4]. The first function is characterized by the connection between electric, mechanical and acoustic fields. The second function is characterized by the interaction of antenna elements in the acoustic field. The appearance of the acoustic interaction of antenna elements is due to the multiple exchange of radiated and reflected sound waves between them. Through the acoustic field, both functions also interact with each other. The described interactions of processes and fields in sonar antennas depend on many physical factors associated with antennas and their elements: the nature of the electrical excitation of the elements, their type, configuration, size and so on. Naturally, the influence of physical factors limiting the HAS radiation of maximum acoustic power will also depend on the results of the above interactions. We will demonstrate this with the example of possible options for electrical excitation of transducers in antennas.

In HAS for various purposes, in principle, the following options for electrical excitation of emitters are possible:

– frequency independent electric voltage;

– frequency-dependent voltage;

– a combination of both of the above options.

Let us consider qualitatively the influences of the given variants of electric excitation of converters on the formation of power limiting factors.

To date, the most common in the creation of HAS found frequency-independent electrical excitation of their sonar antennas. This is primarily due to simpler technical solutions that can be used in the construction of powerful electronic generators for the paths of HAS radiation [5, 6]. They are divided into electron tube, thyristor and semiconductor. The problem of their work in the composition of the radiation paths of HAS is the wide changes in the input electrical resistance of HAS emitters. In this case, the active component of the input resistance can take negative values [7], which indicates that electrical energy is not taken by the emitters from the generators, but, on the contrary, is generated by the emitters and sent to the generators. The reactive component of the resistance in the frequency range several times changes the capacitive nature on the inductive and vice versa. Naturally, with such electrical excitation of HAS hydroacoustic antennas, the electric field strength is not a factor limiting the maximum power of HAS radiation. Instead, the physical limiting factor of the mechanical field, such as the mechanical dynamic stresses in the piezoceramics of the emitters, comes first.

It is known [5], that these stresses depend on the velocity of oscillations $\dot{w} = -i\omega w$ and are defined by the expression

$$\sigma = \rho_k c_k B,$$

where $\rho_k c_k$ – density and speed of sound in the piezoceramic material of the emitter; B – coefficient determined by the form of oscillations of the emitter; ω – oscillation frequency; w – maximum radial movement of the emitter surface; i – imaginary unit.

It is also known [4, 7, 8] that when the HAS emitters are excited by frequency-independent electric voltage, the oscillation velocities of all HAS emitters differ significantly and depend on the location of the emitter in the hydroacoustic HAS antenna. As an illustration Fig. 1 presents the results of calculations [8] of the amplitude-frequency characteristics of dynamic stresses in the central (1) and extreme (2) emitters of a circular antenna of three emitters in the sector radiation of HAS, (3) − isolated emitter.

Analysis of existing materials, including those listed, shows the following. Electrical excitation of HAS emitters by frequency-independent electric voltage not only negatively affects the energy efficiency of HAS, but also significantly complicates the coordination of generators with sonar antennas in the paths of HAS radiation. Significant differences in the oscillating speeds of HAS emitters do not allow to realize the full potential of HAS in terms of radiated power.

Since the levels of mechanical dynamic stresses are proportional, according to expression (1) to the values of

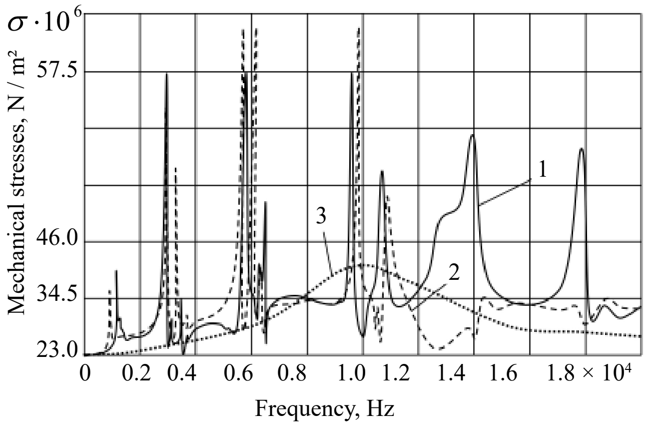

Fig. 1. Amplitude-frequency characteristics of dynamic stresses in the central (1) and extreme (2) emitters of a circular sonar antenna, as well as in an isolated emitter (3)

the oscillating speeds of the HAS emitters, there is always an oscillating speed, which is the limit $\dot{w}_{доп}$ and above which comes the mechanical destruction of the radiator structure. The factor of limiting the acoustic power emitted by HAS by a mechanical field comes into force. Usually such emitters are extreme emitters in sonar antenna arrays, because they are acoustically underloaded in arrays by acoustic interaction of their emitters and have the highest oscillating speed. Medium emitters emit less acoustic energy into the environment than the extreme ones and central emitters may not absorb energy at all, but absorb energy from the acoustic field. This is due to the low energy efficiency of HAS at frequency-independent voltage generated by HAS generators to excite the emitters of its sonar antenna.

The above analysis shows that increasing the energy efficiency of HAS can be achieved by establishing control over the value of the limiting factor of the mechanical field. For this purpose it is necessary to create in HAS such conditions of electric excitation of its emitters at which oscillating speeds of all emitters of the hydroacoustic antenna of HAS will be identical. Moreover, their value can be taken equal to the maximum allowable speed $\dot{w}_{доп}$. Analysis of the data published in the literature [4] shows that the maintenance in HAS of the same oscillating speeds of all emitters allows to:

– increase the radiated acoustic power of both individual emitters of the sonar antenna and the sonar antenna as a whole;

– exclude the effect of the transition of radiators from the mode of acoustic energy radiation to the mode of its absorption from the acoustic field;

– reduce the non-uniformity of frequency dependences of radiation impedances of HAS sonar antenna elements;

– reduce the heterogeneity of the acoustic field in the near zone of the hydroacoustic antenna HAS.

The given approach to electric excitation of HAS emitters allows to protect them effectively from the mechanical overloads caused both by cyclic change of exciting voltages from the electric field and cavitation loadings from the acoustic field. This is a positive of the chosen approach. At the same time, it should be noted that the increase in the energy capacity of HAS in this way is associated with the emergence of two extremely negative physical factors.

The first is a significant increase in all electrical voltages exciting the emitters. This is especially true for the frequency ranges below and above the natural frequencies of the mechanical resonance of the HAS emitters, due to the significant increase in the natural mechanical impedances of the piezoceramic shells of the emitters in these frequency ranges.

The second factor is the appearance of a certain dependence of excitation voltages on frequency.

As a demonstration of the above features of the behavior of exciting electrical voltages in the case of a cylindrical antenna formed of five coaxial piezoceramic shells, there are curves in Fig. 2 [4], where 1, 2, 3 and 1′, 2′, 3′ correspond to the modulus and phase of the exciting electrical voltages of the central (3), middle (2, 4) and extreme (1, 5) shells.

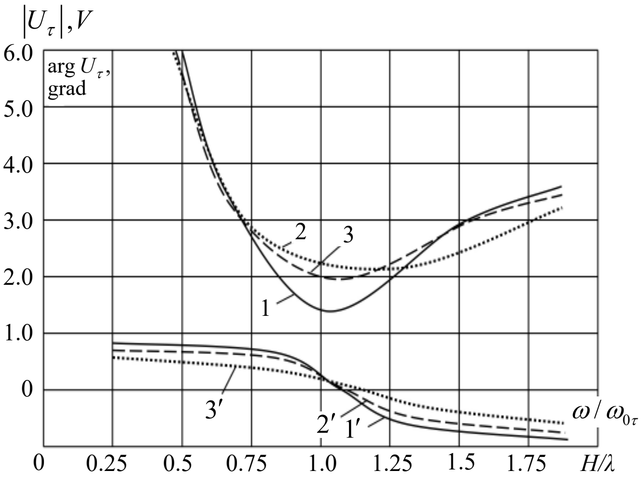

Fig. 2. Amplitude-frequency and phase-frequency dependences of electric excitation voltages of a five-element cylindrical antenna with the same oscillating speed of the rings

Thus, increasing the efficiency of HAS radiation by exciting its emitters with the same oscillating speed is possible under two conditions − the creation of frequency-dependent electrical excitations of HAS emitters and a significant increase in excitation voltage, that is the physical factor of limiting HAS radiation power.

The above analysis of the possibility of meeting these requirements with existing in acoustics thyristor and semiconductor generators shows that they do not meet the formulated requirements. Lamp generators can fully meet these requirements. But their inherent shortcomings − large size, low efficiency, large amounts of heat, etc., precluded their use in the construction of modern HAS. Thus, the modern technical base is not prepared for the implementation of increasing the acoustic power of HAS by creating frequency-dependent electrical excitation of HAS emitters.

From the point of view of possibilities of practical realization of increase of acoustic power of HAS the compromise variant [4] can be interesting. It is as follows. To avoid a significant increase in the excitation voltage in the HAS and thus control the limiting factor of the electric field, you need to set a certain amount of excitation voltage on one or more HAS emitters and on all HAS emitters to ensure the same oscillating speed. The results of such an experiment (Fig. 3) for a cylindrical hydroacoustic antenna formed of five coaxial rings are presented in [4]. Fixed values of excitation voltages were given for the second and fourth rings and the same oscillating speed was set for all rings.

Analysis of the results shows that in a given frequency range exceeding one and a half octaves, a small (20 %) increase (Fig. 3c) in the excitation voltage occurs only for the central (3) ring, and the speed of all rings (Fig. 3b) are the same. Here are the powers emitted by each of the rings (curves 1, 2, 3) and the antenna as a whole. The above indicates that the increase in the effective radiation power of HAS can be done by technical implementation of a compromise version of its radiating path.

THE STATE OF METHODOLOGICAL SUPPORT FOR WAYS TO INCREASE THE ENERGY EFFICIENCY OF HAS

For the practical implementation of the above ways to increase the energy efficiency of HAS, you need to have new knowledge in all physical fields that provide radiation to the sound of HAS. This knowledge should be based on the interaction of electric, mechanical and acoustic fields in sound radiation, energy conversion, acoustic interaction of hydroacoustic antenna elements in the formation of energy in the environment and the interaction of the processes of conversion and energy formation. In mathematical terms, all these types of relationships are taken into account by the joint solution of the system of differential equations associated with the respective fields. For HAS with sonar antennas formed from cylindrical sonar radiators with circular polarization, the system of differential equations includes:

– Helmholtz equation describing the oscillatory motion of elastic media inside and outside the converters of the system:

$$\Delta \Phi_{jS} + k_j^2 \Phi_{jS} = 0; \qquad (1)$$

– equations of motion of thin piezoceramic shells of emitters in displacements:

$$\begin{aligned} &\left(1+\beta_S\right)\frac{\partial^2 u_S}{\partial \varphi^2} + \frac{\partial w_S}{\partial \varphi} - \beta_S \frac{\partial^3 w_S}{\partial \varphi^3} = a_S \gamma_S \frac{\partial^2 u_S}{\partial t^2}; \\ &-\frac{\partial u_S}{\partial \varphi_S} + \beta_S \left(\frac{\partial^3 u_S}{\partial \varphi_S^3} - \frac{\partial^4 w_S}{\partial \varphi_S^4} \right) - w_S + \frac{e_{33\,S}}{C_{33\,S}^E} r_S E_{\varphi S} + \frac{a_S}{h_S} q_{rS} = \\ &= a_S \gamma_S \frac{\partial^2 w_S}{\partial t^2}; \end{aligned} \qquad (2)$$

– equations of forced electrostatics for piezoceramics:

$$\vec{E}_S = -grad \psi_S; \quad div \vec{D}_S = 0. \quad (3)$$

In expressions (1) – (3): S – the number of the emitter in the sonar antenna ($S = 1, \ldots, N$) with N elements; j – acoustic field area number ($j = 1$ for the external field; $j = 2$ for internal); Δ – Laplace operator; Φ_{jS} – speed potential S-th emitter in the j-th region; k_j – the wave number of the medium in the j-th region; u_S i w_S – circular and radial components of the vector of displacements of the points of the middle surface of the shell of the S-emitter; $\beta_S = h_S^2 / 12 r_{0S} (1 + e_{33S}^2 / C_{33S}^E \varepsilon_{33S})$; $a_S = r_{0S}^2 / C_{33S}^E$; q_{rS} – external radiation load of the S-th emitter; $C_{33\,S}^E$, $e_{33\,S}$, ε_{33S}, γ_S –

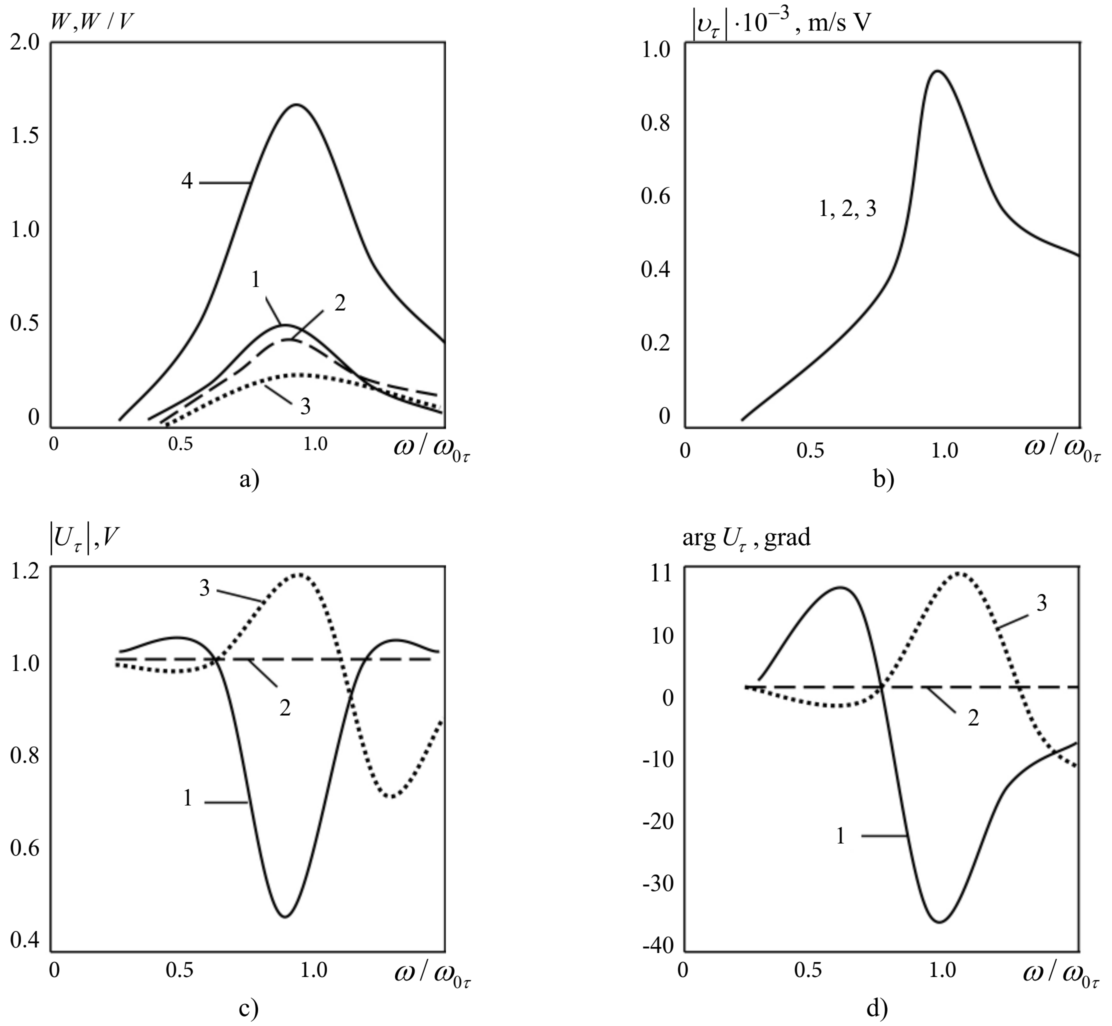

Fig. 3. Frequency dependences of acoustic power (a), oscillating speeds (b), amplitudes (c) and phases (d) of electrical excitation voltages of rings in a five-element cylindrical antenna with a compromise version of electrical excitation of rings and their same oscillating speed

respectively, the modulus of elasticity at zero electric stress, piezoelectric constant, dielectric constant at zero deformation, the density of the material of the S-piezoceramic emitter; $\vec{E}_S$ і $\vec{D}_S$ – vectors of electric field strength and induction in the *S*-th emitter; ψ_S – voltage of electric excitation of the *S*-th emitter; r_{0S} and h_S – the radius of the middle circle and the thickness of the shell of the *S*-th emitter.

The given system of differential equations describes the process of radiation of acoustic energy of HAS with hydroacoustic antennas on the basis of cylindrical converters at all considered schemes of electric excitation of radiators in HAS. The concretization of these schemes is achieved by setting boundary conditions.

When exciters are emitted in HAS frequency-independent electric voltage, the electric field strength in expression (2) is determined by the expression

$$E_{\varphi S} = -\frac{\psi_S M_S}{2\pi r_{0S}}, \ \ S = 1, ..., N, \qquad (4)$$

where M_S – the number of piezoceramic prisms from which the shell of the S-emitter is glued.

Quantitative values of electric, mechanical and acoustic fields in the form of new knowledge and the ability to emit maximum acoustic energy of HAS obtained [4, 7–11] for HAS with antennas in the form of linear sonar antennas with and without screens, flat antennas and circular cylindrical antennas with screens.

When the excitation of HAS emitters frequency-dependent electric voltage in expression (2) radial $\dot{w}_S$ and circular $\dot{u}_S$ oscillating speeds ($\dot{w}_1 = \dot{w}_S = \dot{w}_N$; $\dot{u}_1 = \dot{u}_S = \dot{u}_N$; $S = 1, ..., N$) for all emitters are accepted by default. The desired are values of the electric field strengths of all $S = 1, ..., N$ emitters. To date, the problem is that new knowledge are almost non-existent. Quantitative values for all fields were obtained [4] only for single cylindrical emitters. For arbitrary systems of such emitters, only analytical expressions for calculations of physical fields were obtained [12]. Technically, there are no implemented ways to build electronic generators that generate frequency-dependent excitation voltage.

To excite the HAS emitters with a compromise variant in expression (2) it is necessary to set the voltage for one emitter $E_{\varphi S}$ $(S = 1)$ electric field, and for all HAS emitters $(S = 1, ..., N)$ the same oscillating speeds $\dot{w}_1 = \dot{w}_S = \dot{w}_N$ і $\dot{u}_1 = \dot{u}_S = \dot{u}_N$. Then, when solving the system of differential equations (1) − (3), the electric field voltages of all other emitters and the oscillatory velocities of all HAS emitters will be sought. Unfortunately, today this version of acoustic power is impossible due to lack of necessary new knowledge [4].

CONCLUSIONS

It is shown that in HAS in the mode of echolocation of radiation of maximum acoustic power is limited by a number of physical factors, each of which is associated with a specific physical field that participates in the radiation of sound. These limiting factors include:

– cavitation threshold in the acoustic field;

– dynamic mechanical stresses in a mechanical field;

– electric field strength.

It is established that the influence of each of the limiting factors on the radiated HAS maximum power is determined by the nature of the electrical excitation of the HAS emitters. Three possible variants of electrical excitation of radiators are considered:

– frequency independent electric voltage;

– frequency-dependent electric voltage;

– compromise, which in some way combines the first two options for electrical excitation of HAS emitters.

The positive and negative sides of each of the above options for electrical excitation of HAS emitters influence on the limiting factors in terms of HAS radiation of maximum acoustic power is analyzed.

The existing state of the estimated support for the technical implementation of all three possible options for electrical excitation of HAS emitters when it emits maximum acoustic power is determined.

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АНАЛІЗ МОЖЛИВИХ ШЛЯХІВ ТЕХНІЧНОЇ РЕАЛІЗАЦІЇ ПОТУЖНОГО АКУСТИЧНОГО ВИПРОМІНЮВАННЯ ГІДРОАКУСТИЧНИМИ СТАНЦІЯМИ

Збільшення дальності дії гідроакустичних станцій визначається можливостями збільшення ефективного випромінювання ними акустичних потужностей. Але ці можливості обмежуються рядом фізичних факторів, пов'язаних з електричними, механічними і акустичними полями випромінювачів гідроакустичних станцій. Кожне із вказаних фізичних полів створює для гідроакустичної станції свої обмежуючі фактори в режимі випромінювання енергії. В акустичному полі обмежуючим фактором виступає явище кавітації і пов'язаний з ним поріг кавітації рідини. Це обумовлює зростання механічних напружень в конструкціях гідроакустичних перетворювачів. Наявність механічного поля є причиною появи фізичних факторів, обмежуючих величину випромінювання, оскільки п'єзокераміка критична до розтягуючих зусиль. Максимальна випромінювана потужність визначається максимальною електричною потужністю, яку можна «закачати» в п'єзокерамічний перетворювач. Остання ж обмежується допустимими значеннями напруженості електричного поля. Саме їх величина є обмежувальним фізичним фактором зі сторони електричного поля. Наявність при випромінюванні звуку процесу перетворення електричної енергії в механічну, *а механічної в акустичну обов'язково породжує появу теплового поля, обумовлюючого розігрів п'єзокерамічних перетворювачів. Визначено ці обмежуючі фізичні фактори і встановлено зв'язок їх впливу на величину випромінюваної потужності гідроакустичної станції. Показана залежність цього впливу від шляхів технічної реалізації електричного збудження гідроакустичних випромінювачів. Проведено якісний аналіз переваг і недоліків трьох принципово різних шляхів електричного збудження випромінювачів при збільшенні ними випромінюваної потужності. Встановлено існуючий стан розрахункового забезпечення практичної реалізації наведених шляхів збільшення випромінюваних потужностей гідроакустичних станцій.*

Ключові слова: *гідроакустична станція, акустична потужність, фактори обмеження потужності, збуджуючі напруги.*

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