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SPATIAL SELECTIVITY OF NAVIGATION AND SPECIAL HYDROACOUSTIC STATIONS

It is shown that the requirements for the spatial selectivity of several hydroacoustic stations for navigation and particular purposes necessitate using horn hydroacoustic antennas as part of the stations. Physical and computational models of horn antennas formed from a cylindrical transducer and two truncated cones on its ends have been developed. By the method of partial domains in the spherical coordinate system, considering the diversity of the interaction process of emitted and scattered sound waves, the boundary problem of determining the acoustic fields formed by such stations has been solved. Analytical relationships have been obtained, and a comprehensive numerical experiment has been conducted on their basis. Systematized analysis of its results allowed determining the regularities of the behavior of the spatial selectivity of hydroacoustic stations depending on the wave sizes of the transducer and the conical horns of the antenna and their opening angles. The physical reasons for the appearance of specific features in the behavior of the spatial selectivity of hydroacoustic stations have been established.

Keywords: *hydroacoustic station, acoustic horn, truncated spatial cone, spatial selectivity.*

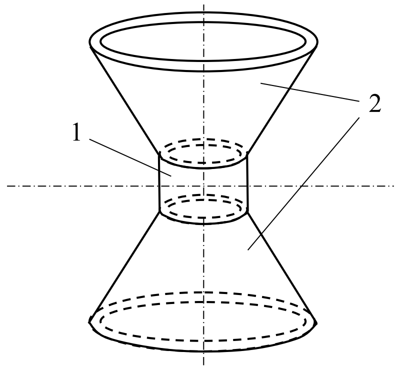
INTRODUCTION

Among many shipborne hydroacoustic stations (HAS), some form a spatial selectivity of a particular type [1, 2]: navigation HAS, HAS for detecting the presence of a hydroacoustic signal, HAS for setting interferences. Such HAS should provide practical implementation of two conditions. The first is the creation of spatial selectivity only in the vertical plane and its absence in the horizontal plane. The second condition is the stability of parameters in a wide range of operating frequencies. To ensure such conditions are created, the HAS should include hydroacoustic antennas that meet the above requirements. Such antennas have hydroacoustic antennas with acoustic screens like a horn. The presence of an acoustic horn of the appropriate shape in the design of the hydroacoustic antenna allows [3, 4] to stabilize the directional properties of the antenna in a wide frequency range, and the values of their technical parameters can be achieved by choosing the required configuration of acoustic horns.

Analysis of published materials indicates that relatively few works have been dedicated to horn antennas in hydroacoustics. Their list can be found in the publication [4]. Therefore, this work aims to present the research results on the directional properties of hydroacoustic antennas with a horn of special design.

FORMULATION AND SOLUTION OF THE WAVE PROBLEM

Let's consider the sound fields of a horn hydroacoustic antenna, the physical model of which is presented in Fig. 1.



F i g . 1. Schematic of the construction of a horn hydroacoustic antenna

The antenna is constructed of a hydroacoustic transducer 1 and an acoustic horn 2. A cylindrical piezoceramic transducer can be used as the hydroacoustic transducer, the shell of which is a solid or sectioned cylinder. Its internal cavity may be vacuumed or filled with gas or liquid. The electrical excitation of the transducer is carried out at the zero mode of its mechanical vibrations, which ensures the uniformity of the amplitude and phase of the oscillatory velocity of the shell's surface at any point. Due to this, the HAS with such an antenna does not provide spatial selectivity in the horizontal plane.

The construction of the Acoustic Horn 2 consists of two parts. Each of them has the configuration of a truncated spatial cone. Typically, the diameter of the upper part of the truncated cone, which is near the hydroacoustic transducer, is the same as the diameter of the transducer. The choice of the near diameter to the hydroacoustic transducer of the lower part of the lower truncated cone is somewhat more complicated. As known [4–6], an acoustic horn is used to form the spatial selectivity of both the hydroacoustic antenna and the HAS. For the horn configuration shown in Fig. 1, this spatial selectivity is formed in the plane of the longitudinal axis of the antenna. If the acoustic horn has radial symmetry, this spatial selectivity is also radially symmetrical. Suppose the upper and lower parts of the horn are identical. In that case, the hydroacoustic antenna's directivity characteristic in the longitudinal section's plane is also symmetrical relative to the perpendicular to the longitudinal axis of the antenna. To form an asymmetrical directivity characteristic, it is necessary to disrupt the identity of both truncated horns either by their sizes and opening angles or by the physical properties of the materials from which they are made. In this case, it is possible to form a directivity characteristic of a given special shape. Sound-reflecting materials can be used as materials for acoustic horns.

Acoustic soft materials can be various types of air-filled rubber, for example, 10087, 51-1415 [7, 8]. As acoustically rigid materials, gray cast iron or other metals are used, which ensure the exclusion of the formation of bending waves in the structures of horns.

Currently, there are several approaches to developing computational models for horn hydroacoustic antennas, all of which are related to considering the physical properties of such antennas. Such features include [6]:

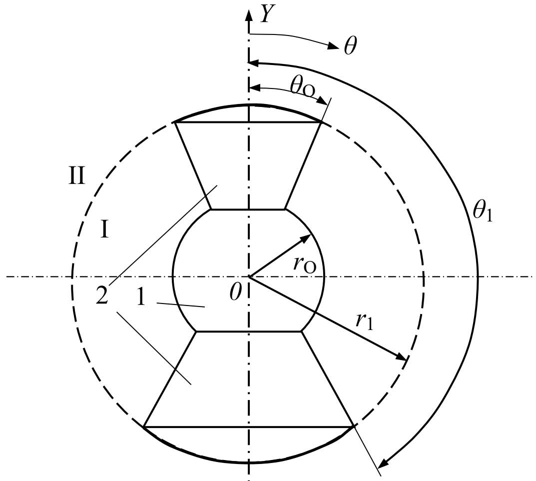
- interaction of physical fields – electrical, mechanical, and acoustic in the process of converting electrical field energy into acoustic in piezoceramic environments of hydroacoustic transducers in the emission mode [9, 10];
- interaction in the formation of acoustic fields created by separate parts of the horn antenna structures due to the multiple processes of emission and reflection of sound waves from these parts;
- interaction of energy conversion processes and their formation in surrounding environments.

In computational terms, this is associated with a combined solution of a system of three differential equations:

- Helmholtz equation for harmonic processes;
- equations of electro-elastic vibrations of elastic piezoceramic shells;
- state equations of piezoceramics.

Since only the spatial selectivity of horn hydroacoustic antennas is considered, we will limit ourselves to considering the acoustic interaction of parts of the horn antenna structure when constructing its computational model. Such a computational model is presented in Fig. 2.

The sound source of the computational model of the horn hydroacoustic antenna is made in the form of sphere 1, and the acoustic horn 2 is in the form of two spherical sectors, which are coaxially placed. Assume that the entire surface of the acoustic horn is covered with acoustically soft material. Then, the boundary conditions can be formulated as follows:



F i g . 2. Computational model of a horn hydroacoustic antenna

$$\Phi = 0;\ \theta = \theta_O;\ \theta = \theta_1;\ r_O \le r \le r_1; \quad (1)$$

$$\Phi = 0;\ 0 \le \theta \le \theta_O;\ \theta_1 \le \theta \le \pi;\ r = r_1; \quad (2)$$

$$\vartheta = \vartheta\_O f(\theta);\ \theta\_O \le \theta \le \theta\_1;\ r = r \le O, \quad (3)$$

where Φ and ϑ – velocity potential and standard component of the oscillatory velocity of the antenna; ϑ_O – velocity amplitude at the point of application; $f(\theta)$ – velocity distribution function.

The solution to the formulated problem will be carried out by the domain decomposition method [4].

We will divide the entire field existence area into two partial areas (Fig. 2):

– *I* area $\theta_O \le \theta \le \theta_1$; $r_O \le r \le r_1$;

– *II* area $0 \le \theta \le \pi$; $r \ge r_1$.

In this case, the coordinate surface $r = r_1$ serves as the boundary dividing these areas. The velocity potential the horn antenna creates can be represented through the velocity potentials in each indicated area. Their general form is determined by the method of eigenfunctions [1]:

$$\Phi_I = \sum_{\nu}^{\infty} \left[A_\nu i_{m_\nu}(kr) + B_\nu n_{m_\nu}(kr) \right] \cdot T_{m_\nu}(\cos\theta); \quad (4)$$

$$\Phi_{II} = \sum_{n}^{\infty} S_n h_n^{(2)}(kr) P_n(\cos\theta), \quad (5)$$

where $\nu = 1, 2, 3 ...$; $n = 1, 2, 3 ...$; A_ν, B_ν, S_n – complex coefficients; $i_{m_\nu}(kr)$, $n_{m_\nu}(kr)$, $h_n^{(2)}(kr)$ – Bessel, Neumann and second kind Hankel spherical functions, respectively;

$$T_{m_\nu}(\cos\theta) = P_{m1}(\cos\theta) + D_\nu Q_{m_\nu}(\cos\theta); \quad (6)$$

D_ν – real coefficient; $P_{m_1}(\cos\theta), P_n(\cos\theta)$ – first kind Legendre functions; $Q_{m_\nu}(\cos\theta)$ – second kind Legendre functions; time dependence is chosen in the format $e^{i\omega t}$.

Expression for the velocity potential Φ_I in area *I* satisfies the Helmholtz equation for all values D_ν and m_ν. An appropriate choice of these values makes achieving conformity with the boundary conditions possible (1). Condition (3) allows establishing a relationship between the coefficients A_ν and B_ν using the relationship:

$$-k\frac{\partial \Phi_I}{\partial(kr)} = \vartheta_O f(\theta);\ \theta_O \le \theta \le \theta_1; r = r_O; \qquad (7)$$

and the properties of completeness and orthogonality of functions $T_{m_\nu}(\cos\theta)$ on the interval $\theta_O \le \theta \le \theta_1$. Omitting the intermediate expositions, we obtain:

$$B_\nu = \frac{L_\nu - A_\nu i'_{m_\nu}(kr_O)}{n'_{m_\nu}(kr_O)}; \qquad (8)$$

where $L_\nu = -\dfrac{\vartheta_O \int_{\theta_O}^{\theta_1} f(\theta) T_{m_\nu}(\cos\theta)d\theta}{k\int_{\theta_O}^{\theta_1}\left[T_{m_\nu}(\cos\theta)\right]^2 d\theta}$;

$i'_{m_\nu}(kr_O)$, $n'_{m_\nu}(kr_O)$ – derivatives of the Bessel and Neumann spherical functions to the argument kr at $r = r_O$.

Considering expression (8), the relationship for the velocity potential Φ_I (4) will transform into the form:

$$\Phi_I = \sum_\nu^\infty \left[A_\nu \Delta_\nu(kr) + L_\nu \frac{n_{m_\nu}(kr)}{n'_{m_\nu}(kr_O)}\right]\cdot T_{m_\nu}(\cos\theta); \qquad (9)$$

where $\Delta_\nu(kr) = i_{m_\nu}(kr) - \dfrac{i'_{m_\nu}(kr_O)}{n'_{m_\nu}(kr_O)} n_{m_\nu}(kr)$.

To determine the remaining unknowns in relationships (5) and (6), we will use such functional equations that combine the conditions of field continuity on the boundary of the partial areas and the boundary condition (2):

$$\Phi_{II} = \begin{cases}\Phi_I;\ \theta_O \le \theta \le \theta_1;\ r = r_1;\\ 0;\ 0 \le \theta \le \theta_O;\ \theta_1 \le \theta \le \pi;\ r = r_1;\end{cases} \qquad (10)$$

$$\frac{\partial \Phi_{II}}{\partial(kr)} = \frac{\partial \Phi_I}{\partial(kr)};\ \theta_O \le \theta \le \theta_1;\ r = r_1. \qquad (11)$$

Algebraization of these functional equations, based on the properties of completeness and orthogonality of functions $P_n(\cos\theta)$, $T_{m_\nu}(\cos\theta)$ on the corresponding intervals, leads to the following infinite system of linear algebraic equations:

$$\begin{cases} S_n h_n^{(2)}(kr_1) - \dfrac{1}{N_n}\sum_\nu^\infty A_\nu \Delta_\nu(kr_1) N_{n\nu} = \\ = \dfrac{1}{N_n}\sum_\nu^\infty L_\nu N_n \dfrac{n_{m_\nu}(kr_1)}{n'_{m_\nu}(kr_O)}; \\ A_\nu \Delta'_\nu(kr_1) - \dfrac{1}{N_\nu}\sum_n^\infty S_n h_n^{(2)}(kr_1) N_{n\nu} = -L_1 \dfrac{n_{m_\nu}(kr_1)}{n'_{m_\nu}(kr_O)}, \end{cases} \qquad (12)$$

where $N_n = \int_0^\pi \left[P_n(\cos\theta)\right]^2 d\theta$; $N_\nu = \int_{\theta_O}^{\theta_1}\left[T_{m_\nu}(\cos\theta)\right]^2 d\theta$;

$N_{n\nu} = \int_{\theta_O}^{\theta_1} T_{m_\nu}(\cos\theta) P_n(\cos\theta)d\theta$; $\Delta_\nu(kr_1) = i_{m_\nu}(kr_1) - \dfrac{i'_{m_\nu}(kr_O)}{n'_{m_\nu}(kr_O)} n_{m_\nu}(kr_1)$; $\Delta'_\nu(kr_1) = i'_{m_\nu}(kr_1) - \dfrac{i'_{m_\nu}(kr_O)}{n'_{m_\nu}(kr_O)} n_{m_\nu}(kr_1)$.

The coefficients of the system (12), expressed by definite integrals, can be calculated in the actual form if integral relationships for Legendre functions [2] are used.

To obtain quantitative calculation results, it is necessary to determine the eigenvalues m_ν and coefficients D_ν, which are included in the expression (6). Based on relationships (9) and (1), we obtain the following system of transcendental equations for determining these quantities:

$$\begin{cases} P_{m_\nu}(\cos\theta_O) - D_\nu Q_{m_\nu}(\cos\theta_O) = 0; \\ P_{m_\nu}(\cos\theta_1) - D_\nu Q_{m_\nu}(\cos\theta_1) = 0. \end{cases} \qquad (13)$$

The procedure for their solution is given in the work [3].

RESEARCH RESULTS AND THEIR DISCUSSION

Let's determine the directional properties of HAS with horn antennas, which are determined by these antennas. For this, we will use the asymmetric representations of Hankel spherical functions for large values of the argument. Then, expression (5) for determining the acoustic field in the far zone of the antenna will take the form:

$$\Phi_{II} \simeq \frac{e^{j\left(kr - \frac{\pi}{2}\right)}}{kr}\sum_{n=0}^N S_n e^{j\frac{\pi}{2}n} P_n(\cos\theta); \quad kr \gg 1, kr \gg N. \qquad (14)$$

Taking into account (14), the approximate expression for the normalized directional pattern will take the form:

$$R(\theta) = \frac{\left|\sum_{n=1}^N S_n e^{j\frac{\pi}{2}n} P_n(\cos\theta)\right|}{\left|\sum_{n=0}^N S_n e^{j\frac{\pi}{2}n} P_n\left(\cos\frac{\pi}{2}\right)\right|}. \qquad (15)$$

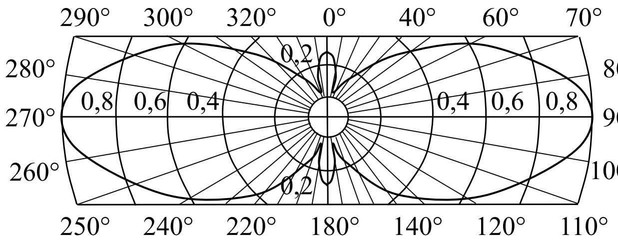
The upper limit of the sums in (15) is determined by the solved finite system's order (12). The concentration coefficient of the horn antenna can be calculated by the known formula [5]:

$$K = 2\left[\int_0^\pi R^2(\phi)\sin\theta d\theta\right]^{-1}. \qquad (16)$$

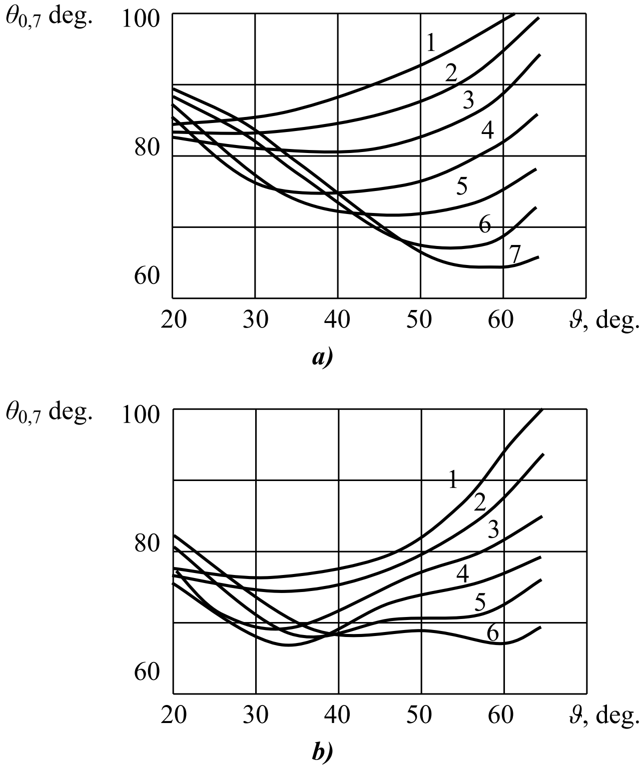
The directional properties of the investigated horn antenna will be studied based on the calculated directivity patterns obtained for a wide range of wave sizes and geometric characteristics of this antenna. In this case, we will limit ourselves to considering one of the important, from a practical point of view, cases when $\theta_1 = \pi - \theta_O$, when the conical acoustic horn is symmetrical relative to the plane $\theta = \frac{\pi}{2}$.

The range of changes in the wave sizes of the radius of the spherical emitter kr_O was chosen within 1,5–4,5. The upper boundary of the wave sizes of the conical horn kr_1 is limited to the value of 17, and the lower boundary is chosen from the condition $kr_1 > kr_O$. The angle θ_O changes within the range from 20° to 60°. All calculations assumed that the spherical emitter is pulsating, i. e., the function $f(\theta)$ = const. The number of unknowns S_n and A_n, retained in the system (12) when it is numerically solved, was 24. As the main parameters, with the help of which we will describe the directional properties of the antenna, we choose the width of the main lobe $\theta_{0,7}$ (at the level of 0,7 from the maximum value) and the concentration coefficient K.

The results of the calculations are presented in Figs. 3−5. Analyzing the spatial selectivity of HAS with a horn antenna based on the directivity diagram of its horn antenna, it is necessary to note their common feature – the presence of additional lobes in the direction of the antenna's axis of symmetry (Fig. 3). These «axial» lobes appear due to the scattering of the sound wave created by the antenna's source on the annular edges (flanges) of the horn. Due to the complete symmetry of the antenna, the edge waves that are formed are in phase in the direction of the OY axis (Fig. 2), which leads to an increase in the pressure level in these directions.



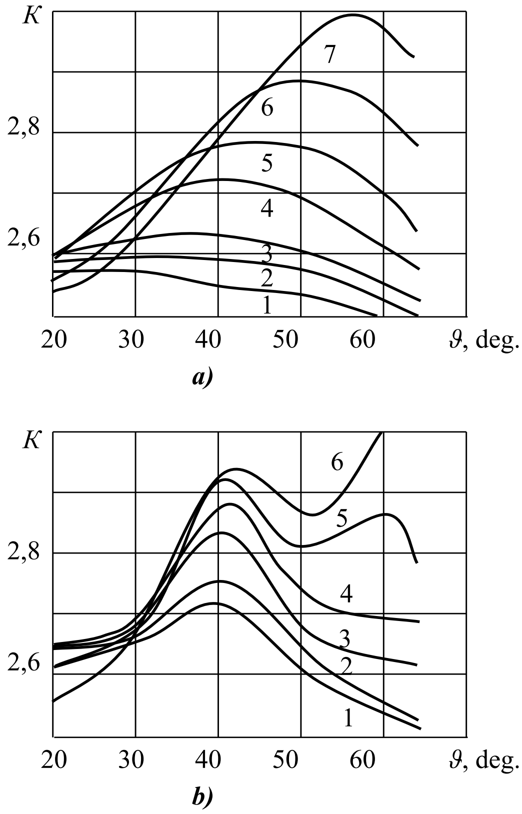
F i g . 3. Typical normalized spatial selectivity of HAS with a horn antenna in the longitudinal plane of the antenna with computational parameters: $kr_O = 3{,}14$; $kr_1 = 8{,}54$; $\theta_O = 60°$; $\theta_1 = \pi - \theta_O$



F i g . 4. Dependencies of the angle θ_O changes in the width of the main lobe of spatial directivity $\theta_{0,7}$ of HAS with a horn antenna with computational parameters:

a): $kr_O = 1{,}6$; $\frac{r_1 - r_O}{\lambda} = 0{,}4$ (curve 1); 0,5 (curve 2); 0,6 (curve 3); 0,86 (curve 4); 1,1 (curve 5); 1,6 (curve 6); 2,0 (curve 7);

b): $kr_O = 4{,}52$; $\frac{r_1 - r_O}{\lambda} = 0{,}4$ (curve 1); 0,14 (curve 2); 0,38 (curve 3); 0,65 (curve 4); 1,14 (curve 5); 1,5 (curve 6)



F i g . 5. Dependencies of the angle concentration coefficient of HAS with a horn antenna with computational parameters:

a): $kr_O = 1{,}6$; $\frac{r_1 - r_O}{\lambda} = 0{,}4$ (curve 1); 0,5 (curve 2); 0,6 (curve 3); 0,86 (curve 4); 1,1 (curve 5); 1,6 (curve 6); 2,0 (curve 7);

b): $kr_O = 4{,}52$; $\frac{r_1 - r_O}{\lambda} = 0{,}4$ (curve 1); 0,14 (curve 2); 0,38 (curve 3); 0,65 (curve 4); 1,14 (curve 5); 1,5 (curve 6)

The dependencies presented in Figs. 4−5 provide the possibility of establishing the properties and peculiarities of the directivity diagram of the horn antenna and, consequently, the spatial selectivity of HAS. One of the main properties is the significant dependence of the parameters characterizing the directivity diagram on the angle θ_O. With an increase in the angle θ_O for most values of $\frac{r_1 - r_O}{\lambda}$ there is initially a narrowing of the main lobe, a decrease in the level of the «axial» lobe, and an increase in the concentration coefficient. Upon reaching a particular value of $\theta_O^{(1)}$, the indicated parameters take extreme values (values of $\theta_{0,7}$ and σ are minimal, and K takes maximum values). Further growth of the angle θ_O leads to the reverse process – the main lobe expands, the level of the «axial» lobe increases, and the concentration coefficient decreases. An essential feature of this is that with the growth of the wave size of the horn, the angle $\theta_O^{(1)}$ increases.

The property mentioned above can be given the following physical explanation. There are significant phase distortions at small angles θ_O in the horn aperture (due to the sphericity of the wavefront), which determine the relatively large width of the main lobe and the low concentration coefficient. With an increase in the angle θ_O the phase distortions in the horn aperture decrease, leading to the sharpening of the main lobe and an increase in the concentration coefficient. This process can continue up to a specific limit until the decrease in the horn aperture begins to have an effect. This last circumstance ultimately leads again to an increase in the value of $\theta_{0,7}$ and a reduction in the value of K.

Another property of the spatial selectivity of HAS with a horn antenna is that with the growth of the wave size of the horn, there is a significant sharpening of the main lobe, a decrease in the «axial» lobes, and an increase in the value of K. This property is most evident at medium and large angles θ_O.

As is known [3], horn antennas have the property of stabilizing directivity diagrams within a specific frequency range. Analysis of the curves in Figs. 4 and 5 allows us to establish another essential feature of HAS with horn antennas. It consists of the fact that at specific values of the angles θ_O of the horn aperture and the ratios $\frac{r_1}{r_O}$ the stability of the spatial selectivity of HAS can reach a frequency range of up to 1−1,5 octaves. Such range properties are most pronounced at angles θ_O = 20°–30° and partly at angles θ_O = 40°–60°.

CONCLUSIONS

Among many shipborne HAS (Hydroacoustic Stations), some form a spatial selectivity of a particular type (HAS for detecting the presence of a hydroacoustic signal, HAS for setting interferences). Such HAS have non-directional properties in the azimuthal plane and directional ones in the plane of the angle of location determination. This is achieved by including horn hydroacoustic antennas in the composition of HAS. The selective properties of HAS are defined as the horn antenna, which consists of a cylindrical hydroacoustic transducer and two acoustically soft truncated spatial cones placed on its ends. In the spherical coordinate system, a computational model of such an antenna has been developed using the method of partial domains, and the wave problem of determining its sound fields has been solved. This considers the interaction of acoustic fields formed by different parts of the antenna structure. Such interaction is due to multiple reflections of sound waves emitted by the hydroacoustic transducer and reflected by the horn screen and the transducer itself. The obtained analytical relationships are used for numerical determination of the dependencies of HAS's spatial selectivity on the wave sizes $\frac{r_1 - r_O}{\lambda}$ hydroacoustic transducers and both conical parts of the horn and the angle of its aperture θ_O at the apexes of the cones. It has been established that with an increase in the angle θ_O for most values of $\frac{r_1 - r_O}{\lambda}$ there is initially a narrowing of the main lobe of the directivity diagram and an increase in the concentration coefficient of HAS. Then, after a particular value of θ_O, further growth of the angle θ_O causes the reverse process. The physical reasons for such behavior of HAS's spatial selectivity have been determined. It also established the dependence of its stabilization at specific values of θ_O and $\frac{r_1}{r_O}$ in the frequency range of 1−1,5 octaves.

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ПРОСТОРОВА ВИБІРКОВІСТЬ НАВІГАЦІЙНИХ І СПЕЦІАЛЬНИХ ГІДРОАКУСТИЧНИХ СТАНЦІЙ

Ряд корабельних гідроакустичних станцій формують просторову вибірковість спеціального виду: навігаційні, станції визначення наявності гідроакустичного сигналу, станції постановки завад. Такі гідроакустичні станції мають ненаправлені властивості в азимутальній площині і направлені – в площинні визначення кута місця. Це досягається введенням до складу гідроакустичних станцій рупорних гідроакустичних антен. Визначені вибіркові властивості гідроакустичної станції, рупорна антена якої складається із циліндричного гідроакустичного перетворювача і двох розміщених на його торцях акустично м'яких урізаних просторових конусів. В сферичній системі координат розроблена розрахункова модель такої антени і методом часткових областей розв'язана хвильова задача визначення її звукових полів. При цьому врахована взаємодія акустичних полів, утворених різними частинами конструкції антени. Така взаємодія обумовлена багатократним перевідбиттям звукових хвиль, випромінених гідроакустичним перетворювачем і відбитих рупорним екраном і самим перетворювачем. Отримані аналітичні співвідношення використані для чисельного визначення залежностей просторової вибірковості гідроакустичних станцій від хвильових розмірів гідроакустичних перетворювачів і обох конусних частин рупора та кута його розкриву при вершинах конусів. Встановлено, що при збільшенні кута розкриву для більшості значень хвильових розмірів спочатку має місце звуження основної пелюстки діаграми направленості та збільшення коефіцієнту концентрації гідроакустичної станції, а потім, після певного значення кута розкриву, подальше зростання кута розкриву обумовлює зворотній процес. Визначені фізичні причини такої поведінки просторової вибірковості гідроакустичної станції. Встановлена також залежність її стабілізації при певних значеннях кута розкриву і співвідношення радіусів сферичного випромінювача і конусного рупора в діапазоні частот 1−1,5 октави.

Ключові слова: *гідроакустична станція, рупор акустичний, урізаний просторовий конус, просторова вибірковість.*

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