Directivity of hydroacoustic systems with parametric array in marine conditions

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Abstract. The paper presents the results of generalization of theoretical and experimental studies of the influence of hydrophysical inhomogeneities on the directional characteristics of the parametric array in the framework of problem solution of improving the efficiency of directional properties of adaptive hydroacoustic systems with parametric emitting arrays. The results of calculations of the directional characteristics of the parametric array obtained on the basis of the Khokhlov-Zabolotskaya-Kuznetsov model are compared with the results of experimental measurements of the directional properties of the parametric array. The normalized dependence of the width of parametric array beam pattern was obtained on the reduction of the difference frequency relative to the central frequency of the pump waves from 5 to 16 times. The influence of the sound velocity change on the direction properties of the parametric array was estimated. The normalized dependence of the width of beam pattern of the parametric array on the value of the sound velocity at the surface of the pump transducer was obtained.

1. Introduction

The possibility of nonlinear effects application in adaptive hydroacoustic systems with parametric radiation mode for bottom and subbottom profiling attracts the attention of specialists from different countries [1-3]. The use of parametric arrays in hydroacoustic equipment makes it possible to increase the information content and accuracy when detecting and determining the coordinates of underwater objects, to obtain additional features for recognition due to their high directivity and low level of the side lobes [4].

The development of hydroacoustic systems with parametric radiating arrays requires taking into account real oceanological conditions, such as fluctuations in sound velocity, temperature and salinity of water, seasonal dependence of the profile of the vertical distribution of sound velocity, the sound reflection coefficient from the bottom, the volume backscattering coefficient and a number of other features [5].

In comparison with linear sonar systems the ones with parametric arrays represent qualitatively innovative tool for ocean research due to the number of unique technical characteristics, such as high directivity at low frequencies at relatively small aperture sizes of the primary transducer, constant width of the directional characteristics in the operating frequency band [3, 4].
2. Problem statement
In practical implementation high efficiency in hydroacoustic systems with parametric arrays is achieved in the case of the formation of highly directional radiation. The beam pattern $R_{\theta}$ of such array in the parametric mode is well described by the expression [4]:

$$R_{\theta} = \exp\left(-\frac{(k1 + k2 \cdot a \cdot \theta)^2}{6}\right),$$

where $k1, k2$ – wave numbers at pump frequencies and $a$ – transducer aperture.

Theoretical consideration of the problem allows systematizing the phenomena that determine the process of nonlinear interaction of acoustic waves, as well as considering a number of hydrophysical inhomogeneities that have the greatest impact on the direction of hydroacoustic systems with parametric arrays in real conditions.

3. Theoretic and experimental studies of the directional properties of a parametric array
As it is noted above, the directional characteristic is one of the most important technical characteristics of a parametric array. The primary transducer of the profilograph is, as a rule, a multi-channel array, and each of the channels is a line of individual piezoelectric elements. The distance between the acoustic axes of the elements is the same. Such antenna systems are called equidistant, and their directional properties are determined by the formula [6]:

$$R = \frac{\sin\left(\frac{\pi b}{\lambda} \cdot \sin \alpha\right)}{\frac{\pi b}{\lambda} \cdot \sin \alpha} \cdot \frac{\sin\left(\frac{n \pi d}{\lambda} \cdot \sin \alpha\right)}{n \cdot \sin\left(\frac{\pi d}{\lambda} \cdot \sin \alpha\right)},$$

where $d$ – distance between the phase centers, $b$ – piezoelectric element size.

Figure 1 shows the beam patterns of primary transducer and parametric array calculated from theoretical models based on the Khokhlov-Zabolotskaya-Kuznetsov model. From the directional characteristics shown in Figure 1, it can be seen that there is practically no side field for the parametric array. Figure 2 shows the theoretical characteristics of the parametric array beam pattern $R_{\theta}$ based on the model of Khokhlov-Zabolotskaya-Kuznetsov, as well as the results of experimental studies of the directional properties of the parametric array, for which the wave numbers at the pump frequencies and the size of the aperture of the primary transducer corresponded to the values taken for calculations on the theoretical model. The results of experimental studies shown in Figure 2 confirm the regularities of the formation of directional properties of the parametric array, described in detail in [4].

The analysis of the results of theoretical studies of the formation of directional properties and experimental measurements of the parametric array beam patterns allows determining the approximate range of changes in directional properties in marine conditions. In order to generalize the results of theoretical and experimental studies obtained for various parametric arrays, the normalized values of the parametric array beam pattern width $\Theta_f/\Theta_0$ were compared for the case of reducing the difference frequency $F$ of the parametric array relative to the central frequency of the pump waves $f_0$ in the range $f_0/F$ from 5 to 16. The obtained normalized characteristics of the parametric array beam (1 – theoretical, 2 – experimental) are shown in Figure 3.
Figure 1. Beam pattern: a – linear array of primary transducer; b – parametric array

Figure 2. Parametric array beam pattern: a – theoretical based on the model of Khokhlov-Zabolotskaya-Kuznetsov; b – experimental

Models describing the characteristics of the parametric array in the far field are valid only in a certain area of parameter change [4]. Since the area of nonlinear interaction is a three-dimensional volume, it is necessary to take into account the influence of hydrophysical inhomogeneities on the process of nonlinear interaction and on formation of parametric array characteristics. The results of theoretical studies of the mathematical model of nonlinear interaction of acoustic waves, taking into account the effect of changes in the sound speed on the directional properties of the parametric array, showed that the increase in the sound speed in the medium in addition to reducing the pressure level of the difference frequency wave leads to an expansion of the beam pattern [7]. Two modes of sound velocity modeling in water were investigated. In the first mode, a heat spotlight located near the water surface was used to create a heat flow, which allowed to obtain different distributions of the sound speed in the study of the directional properties of a parametric array with a high-frequency primary transducer. The second mode of operation was intended to create a vertical layer of sound speed change in the study of the antenna with a low-frequency primary transducer. In the bottom part of the hydroacoustic pool a set of tubular heaters was installed, the power of which was regulated and reached 1.5 kW. Above the heaters, a metal
mesh screen with a cell size of about 1.5 mm was installed. Screen provided the creation of a spatial structure for the distribution of water temperature by interrupting the convection flow. It was established experimentally that with sound speed increasing from 1500 m/s to 1540 m/s, the directivity of parametric array is expanded by about 1° for high frequency primary transduser and 0.5° for low-frequency priary transducer with the beam pattern width of primary transducers 6° and 4°, respectively. Figure 4 shows the normalized characteristic of the angular distribution of the sound pressure level of difference frequency wave vs sound speed for high frequency parametric array ($\Theta_{1500} - \text{beam pattern width with sound speed 1500 m/s, } \Theta_i - \text{beam pattern width with sound speed } i, \text{ where } i = 1500; 1520; 1540 \text{ m/s}$).

![Figure 3](image1)

**Figure 3.** Normalized characteristic of beam pattern width vs decrease in difference frequency of parametric array relative to the central frequency of the pump waves

![Figure 4](image2)

**Figure 4.** Normalized characteristic of the change in beam pattern width vs sound speed in water

4. Conclusion
The results of studies of the dependence of the beam pattern width vs decrease in the difference frequency of the parametric array relative to the central frequency of the pump waves showed that the difference between the directional properties in real conditions from the theoretical characteristics of the directivity can be up to 10%. As a result of research, the range of changes in the parametric array beam pattern width varies from 0.5° to 2°. This change is significant for beam pattern width 4°-6°. In the theoretical studies, the value of sound velocity in water was assumed to be constant in the entire field of nonlinear interaction.

The obtained results will improve the efficiency of application of hydroacoustic means with parametric arrays in ocean studies related to the measurements of the backscattering of acoustic waves.
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