EPJ Web of Conferences **254**, 02011 (2021) https://doi.org/10.1051/epjconf/202125402011
STRPEP 2021

Operation of a multi-frequency parametric side-scan sonar in an ice waveguide

Petr Pivnev[1*], *Sergey* Tarasov[1], *Zhu* Jianjun [2], *Vasily* Voronin[1]

[1]Southern Federal University, Taganrog, Russia
[2]Harbin Engineering University, China

Abstract. Hydroacoustic systems for mineral exploration, solving engineering problems and monitoring the ecological state of the world's oceans are currently being intensively developed. However, the practical use of hydroacoustic systems for solving the problems under consideration, operating in the traditional mode, has some significant limitations. These restrictions are largely related to the state of the marine areas in which such work is carried out. Especially little is known about the patterns of propagation and interaction of acoustic waves in marine basins with ice cover. These areas are rich in minerals and intensive shipping is developing in them. Therefore, an important place in acoustic research is occupied by the study of the acoustic properties of the ice cover of the polar regions of the Earth. This is determined by the fact that the ice sheet is a unique constantly collapsing and renewable natural system. In this regard, the conditions for the propagation of acoustic waves are changing. More than 70% of the Arctic basin is covered with ice, the lower boundary of which has significant irregularities with a standard deviation of up to 3 m, so the scattering of acoustic waves at such a boundary is significant and different at different frequencies. The formation of the acoustic field of the hydroacoustic systems used in these conditions is quite complex. Therefore, the task of assessing changes in the characteristics of the field and the use of appropriate hydroacoustic systems for their effective use is urgent.

1 Page layout

One of the tools for studying the bottom relief and bottom sediments is a side-scan sonar (SSS). It allows to us significantly increase the productivity of survey due to the large area of the surveyed space in one measurement cycle. A characteristic feature of the SSS is the shape of the beam pattern: wide in the vertical plane (to provide a wide viewing band of the bottom and the aquatic environment) and narrow in the horizontal plane (to increase the resolution of the locator by angular coordinates). Traditionally, a wide directivity characteristic in SSS is created either by the small wave dimensions of the array in a given plane, or by the using of developed curved array surfaces.

---

* Corresponding author: pivnev@mail.ru

Array with curved surfaces at low frequencies have too large dimensions. Arrays that form a wide directivity due to small wave sizes will not allow placing a large power on the radiating surface. So, the energy potential are reduces. The creation of small-sized arrays in the low-frequency range is possible by using of radiating parametric arrays, whose operation is based on the nonlinear interaction of acoustic waves in an aquatic environment. The interaction of two or more waves propagating in the medium generates waves with combination frequencies, including in the low-frequency range. To profile the bottom and bottom structures or to search for silted objects, it is necessary to use acoustic signals in the low-frequency range for their good penetration into the bottom sediment thickness. Therefore, the low-frequency part of the spectrum of waves generated by a parametric antenna is of interest.

The efficiency of generating secondary waves in a parametric radiating array depends on the concentration of the energy of the pump waves in space, that is, it depends on the width of the directivity characteristic. An increase in the energy of waves in the low-frequency range is associated with an increase in directivity [1]. In SSS, a wide directivity characteristic in a parametric array can be formed by using several small-sized highly directional pumping arrays. In other words, we can apply the approximation of an arc antenna by plane partial pumping arrays with the addition of a low-frequency field in space [2,3].

The total beamwidth will be determined by the beamwidth of the partial array, the number of individual partial pumping arrays, and the angle between them. This design of the parametric arrays provides a wide field of view, when all elements are switched on simultaneously.

At the same time, it can work as a scanning one, when individual converters with a rather narrow beam width, are switched on alternately. To conduct research with a parametric side-scan sonar, a parametric radiating array with a beam width about 25 degrees in the vertical plane and about 3 degrees in the horizontal plane was developed. The antenna consists of five partial pumping arrays with pumping frequencies of 130 and 150 kHz. This makes it possible to form the necessary beam pattern in the horizontal plane. The energy efficiency of such arrays is ensured by the narrow beam patterns of partial arrays in both planes.

2 The use of multicomponent signals to increase the efficiency of radiation at low frequencies

To increase the efficiency of converting the energy of pumping waves into the energy of a difference frequency wave, it is proposed to use the interaction of waves in a multicomponent pump signal [4,5]. At the same time, a multicomponent signal will be understood, as a pumping signal in which the individual components (waves) are separated by frequency from each other at the same frequency, usually equal to the lower difference frequency of the parametric array.

The amplitude of the spectral low-frequency component of the signal generated in the medium will be equal to:

$$P_{-} = \sum_{m=1}^{n-m} P_m \, , \tag{1}$$

Where, P_m is the amplitude of the m-th component of the difference frequency wave. It is equal to:

$$P_m = \sum_{m=1}^{n-m} A_{k,k+m} p_k p_{k+m} \, , \tag{2}$$

n - is the number of components; m - is the component number of the difference frequency signal; p_k, p_{k+m} -are the amplitudes of the interacting components of the pump waves.

$$A_{k,k+m} = B_{k,k+m} I_{k,k+m} \qquad (3)$$

$B_{k,k+m}$ – coefficient that takes into account the characteristics of interacting waves and the parameters of the propagation medium:

$$B_{k,k+m} = \frac{a^2 \varepsilon m \Omega}{8 c_m^4 \rho} \exp\left(-\frac{z}{L_m}\right), \qquad (4)$$

$$I_{k,k+m} = i \cdot \int_0^z \frac{\exp(-\alpha z(1-i\Delta D))}{\left(1-i\frac{z-y}{L_{dm}}\right)+y\left(\frac{2iL_{dm}}{l_{dk}\cdot l_{dk+1}}+\frac{z}{l_{dk}\cdot l_{dk+1}}\right)} dy\ , \qquad (5)$$

where, $l_{dk} = \frac{a^2\omega_k}{2c_k}$, $l_{dk+1} = \frac{a^2\omega_{k+1}}{2c_k+1}$ - the diffraction zones of the pump array by the k-th and k+1- st components of the pump waves; $L_{dm} = \frac{a^2 m\Omega}{4c_m}$ - - the length of the diffraction zone of the difference frequency wave component; $\alpha = \frac{2c_m^3\rho}{b(m\Omega)^2}$ – the attenuation coefficient of the difference frequency wave component;
c_m, c_k, c_{k+1} – the sound velocity of the *m*-th component of the difference frequency wave and the interacting pump waves;
$\Delta D_m = (k_j - k_{j+1} - K_m) l_{zm}$ - characterizes the change in the phase shift between interacting waves at a distance proportional to the attenuation length of the pump waves and determines the period and amplitude of the oscillations of the formed waves of difference frequency.

Analyzing the above expressions, it can be stated that the amplitude of the lowest harmonic of the difference frequency wave during the interaction of a multicomponent signal increases almost proportionally to the number of interacting components of the difference frequency waves (the number of components minus one). Thus, the range of the parametric side-scan sonar is significantly increased. For example, the studies conducted in [6, 7] showed that the use of a six-component pump signal allowed to reach the depth of sounding of the bottom layers five times more than when using a two-component pump signal.

Figure 1 shows the calculated values of the harmonic amplitudes of the difference frequency signal. They obtained by the interaction of a six-component pump signal for different penetration depths of difference frequency signal into the ground. The calculated values, are shown by points combined by curves to illustrate the dependence at the same penetration depths. Curve 1 corresponds to the depth of the layer h = 1 m, 2 – 2 m, 3 – 3 m, 4 – 5 m. The point indicated by the number 5 represents the value of the amplitude of the difference frequency wave with a two-component pump signal.

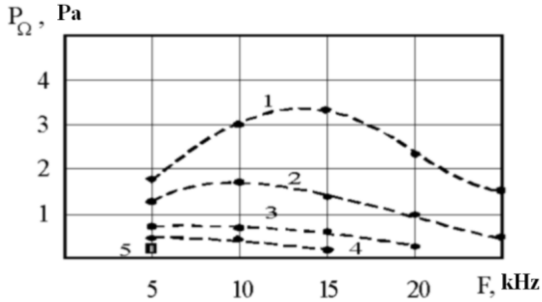

Fig. 1. Amplitudes of harmonic components of the difference frequency signal in the interaction of a six-component pump signal.

The amplitudes of the waves of the second and higher harmonics of the difference frequency also increase significantly. The spectrum of secondary waves is enriched. For sonar, the energy of higher harmonics of difference frequency waves may be used. However, the use of such multicomponent pumping signals requires an increase in the dynamic range of pump wave amplifiers.

3 Features of behaviour of parametric antenna characteristics in an "ice" waveguide

The broad beam pattern of the parametric side-scan sonar in the vertical plane when operating in a waveguide can illuminate a certain area of the water surface. In this case, there is a reflection of both pumping waves from the surface and waves of difference frequency. Let's consider how the combined reflection of these waves affects the field of a reflected wave of difference frequency [8-9]. When interacting waves reflected from the waveguide boundaries, two parametric arrays are formed, as it were. The first is limited by the distance from the pumping array to the reflecting surface. The second array formed by waves reflected from the surface. Moreover, virtual arrays have different interaction characteristics. The second parametric array generates waves of difference frequency due to the interaction of reflected pump waves in a virtual pump array formed as a result of reflection of pump waves from the waveguide boundary. As a result, the signal is formed by summing the difference frequency waves reflected from the waveguide boundary with the difference frequency waves generated after the pump waves are reflected from the waveguide boundaries.

The acoustic resistance of the waveguide boundaries can take different values. These are acoustically rigid boundaries with a reflection coefficient of V=1, acoustically soft boundaries with a reflection coefficient of V= -1 and boundaries with a complex reflection coefficient. In this case, $V=V_1+iV_2$, where V_1 and V_2 are the real and complex part of the reflection coefficient.

Considering only the axial distribution of difference frequency waves, the solution for difference frequency wave in an infinite space can be written in a simplified form through integral exponential function as:

$$P_{-}(0,z_3)=\frac{ip_{01}p_{02}\varepsilon\Omega^2a^2}{8c_0^4\rho_0(i+Bz_3)}e^{\frac{d-iz_3}{i+Bz_3}}\left[E_i\left(\frac{Bz_3+d}{i+Bz_3}\right)-E_i\left(\frac{d-iz_3}{i+Bz_3}\right)\right], \tag{6}$$

where $E_i(z)$ – integral exponential function [8, 9].

In the general case, at an arbitrary angle of incidence, the complex amplitude of the difference frequency wave is determined by the addition of the wave formed before the reflecting boundary with the wave appearing after the reflection of the pump waves with the corresponding phases. In the case of a normal beam incident on the waveguide boundary , it is possible to obtain an expression for the axial distribution of the sound pressure of a difference frequency wave in the form:

$$P_{-}=\frac{ip_{01}p_{02}\varepsilon\Omega VL_{Д}}{2c_0^3\rho_0(i+Bz_3)}e^{\frac{d-iz_3}{i+Bz_3}}\begin{bmatrix}(1-V)E_i\left(\frac{Bh_3z_3+i(h_3-z_3)+d}{i+Bz_3}\right)+\\+E_i\left(\frac{d-iz_3}{i+Bz_3}\right)-VE_i\left(\frac{Bz_3+d}{i+Bz_3}\right)\end{bmatrix}, \tag{7}$$

for V=1, i.e. an acoustically rigid boundary, this expression completely coincides with the previous one and the result turns out to be the same as for an infinite medium. Therefore, it can be conclude that the acoustically rigid boundary does not affect the basic parameters of the parametric array.

In the case of reflection of a parametric array beam from an acoustically soft or impedance boundary, the axial and spatial distribution of the difference frequency wave can changes significantly due to changes in the phase ratios of the difference frequency waves formed before and after the interface.

Experimental studies were conducted on the effect of reflecting boundaries on the field of the parametric array.

Figure 2 shows the transverse distributions of the amplitude of the difference frequency wave obtained experimentally and by calculation in the presence of an acoustically soft boundary. The location of the boundary at an angle of 45 degrees demonstrates the phase changes of the reflected waves of the difference frequency, as if it were an impedance boundary. The experimental curves are shown as solid lines, and the calculated ones are dashed. Measurements and calculations were carried out at different distances from the reflecting boundary - 0.04; 0.08; 0.14; 0.2 and 0.28 m. The distance from the pumping array to the boundary was h = 0.28 m, and the angle of incidence was 45 degrees. Experiments and calculations were carried out for a difference frequency of 150 kHz. Pumping waves with an average frequency of 2.06 MHz were emitted by a pump converter with a diameter of 18 mm [1,2,8,9].

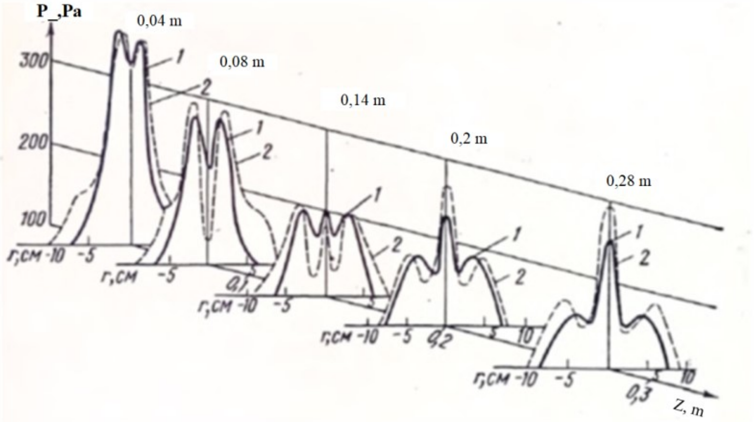

Fig. 2. Experimental (curves 1) and calculated (curves 2) transverse distributions of the difference frequency wave.

The results of the research show that the transverse distributions of waves of difference frequency vary significantly with distance and with a change in the impedance of the reflecting boundary of the waveguide.

Let us briefly consider the scattering and reflection of acoustic waves by the ice boundary of the waveguide [10, 11]. The reflection and scattering of sound by the ice cover depends on the characteristics of the relief of its lower surface and the physical characteristics of the ice. If the sound wave length is much greater than the thickness of the ice cover, then this boundary can be considered as a thin plate lying on an aqueous liquid half-space. Then the reflection coefficient from such a boundary, as shown in [11], is modulo close to unity and the reflection can be considered as from the free surface of the sea, i.e., as from a soft boundary and the arguments about the nature of the field given above are valid. With increasing frequency, the wavelength becomes commensurate with the thickness of the ice cover of the waveguide. At the same time, during reflection, the physical characteristics of the cover begin to significantly affect, in particular, the relief of the lower boundary of the cover, i.e., the upper boundary of the waveguide. If the wavelength becomes commensurate with the terrain irregularities, then they play a major role in the scattering and reflection of waves from the ice cover of the waveguide. The angular dependence of the wave scattering force by the boundary increases significantly. The attenuation of sound in the ice cover also increases with frequency and this affects the amplitude and phase of the sound scattering coefficient by the ice boundary. The same phenomena affect the shape of the scattering indicatrix. It can be approximated by Lambert's law.

4 Conclusions

The paper shows that one of the tools for studying the bottom relief and bottom sediments is a side-scan sonar, which allows to significantly increase the productivity of search operations due to a wide band of the surveyed space. To conduct research with a parametric side-scan sonar, a parametric radiating array with a wide beam pattern in the vertical plane and a narrow one in the horizontal plane was developed. To increase the efficiency of converting the energy of pumping waves into the energy of a difference wave, it is proposed to use the interaction of waves in a multicomponent pump signal. The broad beam pattern of the parametric side-scan sonar in the vertical plane when operating in a waveguide can illuminate a certain area of the surface. At the same time, there is a reflection of both pumping waves from the surface and waves of difference frequency. The effect of the combined reflection of these waves on the field of the reflected wave of difference frequency is considered.

Studies show that when considering the field of a parametric array in a waveguide with an ice boundary, it is necessary to take into account the change in the field depending on the frequency and state of the ice boundary.

References

1. V.K. Novikov, V.I. Timoshenko, Parametric antennas in sonar (Shipbuilding, Leningrad, 1989) (in Russian).
2. V.A. Voronin, S.P. Tarasov, V.I. Timoshenko. Hydroacoustic parametric systems (Rostizdat, Rostov-na-Donu, 2004) (in Russian).
3. S. Tarasov, P. Pivnev, W. Chen, D. Durov, E3S Web of Conf., **127**, (2019) https://doi.org/10.1051/e3sconf /20191270.
4. V.A. Voronin, T.N. Kutsenko, S.P. Tarasov, Izvestiya TRTU, **15**, 1(2000) (in Russian).
5. A.S. Eller , J.A.S.A., **6**, 56 (1974).
6. V.A. Voronin, A.G. Ishutko, T.N. Kutsenko, Izvestiya TRTU, **35**, 6 (2003) (in Russian).
7. P.P. Pivnev, A.V. Voronin, Izvestiya TRTU, **90**, 1 (2009) (in Russian).
8. Karabutova, B.K. Novikov, S.P.Tarasov. Acoustic. Jour., **27**, 3 (1981) (in Russian).
9. L. K. Zarembo, V. I. Timoshenko, Nonlinear acoustics (Publishing House of MSU, Moscow, 1984) (in Russian).
10. V. V. Bogorodsky, V. P. Gavrilo, V. A.Nikitin, Acoustic. Jour., **22**, 2 (1976) (in Russian).
11. G.A. Lebedev, K.K. Sukhorukov. Propagation of electromagnetic and acoustic waves in sea ice (Gidrometizdat, St. Petersburg, 2001) (in Russian).