Monitoring of Bioresources in Shallow Water by Parametric Systems

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Abstract. Hydroacoustic parametric systems and methods of nonlinear acoustics in the study of bioresources in shallow areas of the oceans are considered. Unique characteristics of parametric antennas are given. The general issues of nonlinear interaction of acoustic waves are considered. The features of the interaction and propagation of acoustic waves in shallow water are presented. The characteristics of parametric instruments are presented, and the results of their applications for monitoring bioresources in shallow areas of the oceans are considered.

1. Introduction

Currently, great attention is paid to the research of biological resources of the oceans. One of the main areas of maritime activities in Russia is the development of the oceans, as the most promising source of natural resources, including biological resources. Search and monitoring of biological resources in shallow water is a very urgent task from rational nature management. In modern industrial fisheries, more and more importance is given to the level of technical equipment of the fishing fleet, including hydroacoustic search and monitoring systems.

At present, echo sounders (vertical location) are mainly used to detect and monitor bioresources in shallow water. However, the field of view of the body of water by an echo sounder is very limited. The “scaring effect” that occurs when a ship moves in shallow water has a significant effect on fish behavior. The use of horizontal location devices (“conventional” sonars) with a large field of view is extremely inefficient due to the poor noise environment due to reverberation and multiple reflections of acoustic signals from the bottom and surface \cite{1, 2}.

The use of a traverse-scan parametric sonar will allow fishermen and hydrobiologists to significantly increase the productivity of searching for fishing objects and monitoring bioresources and hydrobionts due to a significant increase in the size of the surveyed area (ten times more compared to echo sounders) \cite{3}.

Hydroacoustic fishing systems with parametric antennas for shallow water have unique characteristics that are difficult to achieve in traditional systems. These characteristics include \cite{4}:

- a wide range of operating (differential) frequencies, which allows the use of complex and broadband signals;
- high resolution in angle, due to the high directivity of the antenna in radiation mode;
- high resolution in range, due to the radiation of broadband signals;
- the constancy of the width of the directivity characteristics of the antenna in the entire range of operating frequencies, due to the feature of the formation of signals at generated frequencies;
– high noise immunity, due to the very low level of lateral radiation of the parametric antenna;
– small dimensions and weight of the pump antenna.

2. The general issue of nonlinear interaction
A parametric antenna is a pump antenna and a section of the water medium where the pump waves interact due to the nonlinear properties of the medium.

To describe the processes of nonlinear interaction of acoustic waves, various mathematical models are used. Including models based on the solution of the Khokhlov-Zabolotskaya-Kuznetsov equation [5, 6]. The mathematical expression obtained based on this model is the most promising and allows us to calculate the amplitude of sound pressure at combination frequencies at any point in space for different parameters of the antenna and signal. The solution of the equation for the amplitude of the acoustic pressure of the signal of differential frequency is obtained in the form [5, 7–9]:

\[
P_\pm = \frac{P_{01}P_{02}e^{\Omega x^2}}{8\varepsilon_0^2\rho_0} \varepsilon \exp(z/L_z) \int_0^z \exp \left[ -\frac{y - \frac{r_v^2}{d + i(y - z_1) + yz_3B}}{d + i(y - z_1) + yz_3B} \right] dy,
\]

where \(P_{01}, P_{02}\) are the pressure amplitudes of the pump waves at the surface of the antenna; \(\varepsilon\) is the nonlinear parameter; \(\Omega = 2\pi f_\pm\) is the difference frequency; \(a\) – is the aperture of the pump radiator; \(L_z = 1/\alpha_\pm\); \(\alpha_\pm\) – is the attenuation coefficient of the difference frequency wave; \(z_3 = z/l_3\), \(z\) – is the coordinate along the wave propagation; \(z_3 = 1/\alpha_{1,2}\); \(\alpha_{1,2}\) – are the attenuation coefficients of the pump waves; \(d = L_D/l_3\), \(B = (L_D/l_3)/(l_{D1}/l_{D2})\), \(r_v^2 = (2\pi^2L_D)/(a^2l_3)\); \(L_D = (a^2\Omega)/(4c_0)\); \(l_{D1}, l_{D2} = (a^2\alpha_{1,2})/(2c_0)\); \(r\) – is the transverse coordinate.

The main problems in detecting underwater objects (including fish clusters) in shallow water and near the surface are the presence of intense reverberation and noise interference. The expression for calculating the energy characteristics of a parametric sonar taking into account noise interference, volume and surface reverb is:

\[
W_u = \frac{2\delta P_{\text{noise}}10^{\gamma_{\text{noise}}/10}}{10^0.05f_{\text{rad}}\sqrt{\gamma_{\text{rec}}} \sqrt{\gamma_{\text{rad}}} \sqrt{F_\pm} e^{\gamma_{\text{rad}}} \sqrt{\gamma_{\text{rec}}}} \left[ \frac{R_\rho}{2x} - \left( \frac{\alpha_\rho \eta_\rho}{2\gamma_{\text{rad}}} \right) - \left( \frac{\delta}{2\gamma_{\text{rec}}} \right) \right]^{2}.
\]

where \(\delta\) – is the signal-to-noise ratio; \(P_{\text{noise}}\) – is the level of noise interference; \(F_\pm = \Omega/2\pi\); \(\alpha = (\gamma + 1)/4\rho_0c_0^3\); \(\gamma_{\text{rad}}\) – is the concentration coefficient in the reception mode; \(\gamma_{\text{rec}}\) – is the concentration coefficient in the radiation mode; \(\tau\) – is the pulse duration; \(I(B, y)\) – is the integral describing the process of nonlinear generation; \(R_\rho\) – is the radius of the equivalent sphere; \(\alpha_\rho, \alpha_\sigma\) – are the volumetric and surface reverb coefficients; \(\eta_\rho, \eta_\sigma\) – are the coefficients of mutual directivity; \(\beta\) – is the attenuation coefficient. By this expression, it is possible to calculate the acoustic power necessary to ensure the detection range in conditions of noise interference and reverberation interference [10, 11].

Detection characteristics in the presence of interference depending on the distance to the target. Detection characteristics in the presence of interference depending on the distance to the target. Figure 1 shows the dependencies of the signal-to-noise ratio \(\delta\) by the detection distance of an underwater object with \(R_\rho = 1\) m at an acoustic power of 70 W radiated at each pump frequency. The effects of volumetric reverb with \(\alpha_\rho = 10^{-6}\) 1/m, surface reverb with \(\alpha_\sigma h = 10^{-3}\) and noise with a level of \(P_{\text{noise}} = 0.01\) Pa are represented by curves 1, 2 and 3, respectively. The signal-to-noise ratio decreases with the combined effects of noise and volumetric reverb (curve 4), noise and surface reverb (curve 5).
Under the influence of all types of interference (curve 6), the signal-to-noise ratio takes the smallest value at all distances and characterizes the possibility of detecting a target with a given probability.

Figure 1. Distance dependences of the signal-to-noise ratio.

3. Traverse-scan parametric systems

The difference (operating) frequencies of the traverse-scan parametric sonars are in the range from 5 to 50 kHz. The viewing range of the space is up to 1000 – 1500 meters, including in shallow water. The scope of such systems is very wide. This is environmental monitoring of the water area and the search for objects (the search for fish clusters, underwater swimmers, etc.) in the water column, including in shallow water. The width of the directivity characteristics of such systems is: vertically from 2 to 6 degrees, horizontally from 2 to 40 degrees. The side lobes of the radiation pattern are practically absent. Figure 2 shows a schematic arrangement of the beams of a traverse-scan sonar.

Figure 2. Schematic arrangement of traverse-scan sonar beams.

The pump antenna consists of six dual-frequency sectors. The directivity characteristics of an antenna consisting of \( n \) elements are determined by the formula [4]:

\[
R_y = \frac{1}{n} \left\{ \sum_{\gamma} \cos[kR\cos(Q_n - \gamma)]R(d)[1 + \cos(Q_n - \gamma)] \right\}^2 + \left\{ \sum_{\gamma} \sin[kR\cos(Q_n - \gamma)]R[\alpha][1 + \cos(Q_n - \gamma)] \right\}^2 ,
\]

where \( [1 + \cos(Q_n - \gamma)] \) – is the blocking ratio; \( n \) – is the number of elements; \( Q_n \) – is the angular coordinate of the element; \( \gamma \) – is the direction of sound arrival; \( R \) – is the radius of the arc on which the elements are located; \( R(\alpha) = R(Q_n - \gamma) \) – directional characteristic of one element; \( k = \frac{\omega}{c} = \frac{2\pi}{\lambda} \).
Figure 3 shows the geometry of the problem (the location of the radiating surfaces of the pump antenna). Figure 4 shows the directivity patterns of a traverse-scan prototype antenna.

Echo signals are received in the sonar by a separate receiving antenna, the output of which is connected to the receiving path. The receiving path is developed taking into account the reception and processing of a short tone signal of various durations and various frequencies and complex broadband signals. The receiving antenna receives powerful reflected pump signals. Therefore, in a sonar, blocking filters for pump frequencies are necessary and the high linearity of the electronic systems of the receiving path is necessary.

![Figure 3. Arc sector.](image)

**Figure 3.** Arc sector.

**Figure 4.** Pump antenna of traverse-scan sonar: a) directivity pattern of one module at a pump frequency of 250 kHz, b) directivity pattern of one module at a difference frequency of 30 kHz, c) The antenna pattern of 6 modules at a differential frequency of 30 kHz.

Figure 5 shows an echogram with the registration of fish aggregations at a distance of about 600 and 400-650 m from the vessel. An echogram was obtained using a prototype of a traverse-scan parametric sonar.

When using broadband signals to monitor large distances in shallow water bodies, it is necessary to take into account the presence of geometric and physical dispersion in the medium. In shallow areas, numerous gas bubbles are present in the water. The frequency dependence of the phase velocity of sound in water is found by the formula [12–15]:

\[ v = \frac{c}{\sqrt{1 + \left(\frac{f}{f_0}\right)^2}} \]

where:
- \( v \) is the phase velocity,
- \( c \) is the speed of sound in water,
- \( f_0 \) is a reference frequency,
- \( f \) is the frequency of interest.
\[ c'(f) = c_0 \left[ 1 - \frac{3UZ^2D}{2k_0a_0^2(D^2 + \delta^2)} \right], \]

where \( U = \frac{4}{3} \pi a_0^2 \) – is the relative volume of air in water, \( n \) – is the number of bubbles, \( a_0 \) – is the radius of the bubble, \( \delta \) – is the damping constant due to radiation, shear viscosity and heat transfer between water and air in the bubble, \( Z = f_0/f \), \( f_0 \) – is the resonant frequency of the bubble, \( f \) – is the frequency of the acoustic wave propagating in the medium, \( D = Z^2 - 1 \), \( k_0 = 2\pi (f/c_0) \) – resonant wave number for gas bubbles.

Figure 5. Echogram of fish clusters at a distance of about 600 and 400-650 m from the vessel.

Transform the formula of the frequency dependence of the phase velocity of sound for the case when a set of bubbles of various sizes is in the medium [7]:

\[ c(f) = c_0 \left[ 1 - \int_{x_1}^{x_2} \frac{3u(a)Z^2D}{2k_0a_0^2(D^2 + \delta^2)} da \right], \]

where \( u(a)da \) – is the relative air volume of the bubbles with radii from \( x_1 \) to \( x_2 \).

The physical and geometric dispersion must be considered when choosing a range of operating frequencies.

4. Conclusion

Parametric sonar systems are a promising tool for exploring the oceans. Currently, this direction of nonlinear acoustics is widely developing, new systems and complexes for searching, monitoring and diagnosing the aquatic environment and bottom soil, including in shallow water, appear. The small size of the parametric systems allows them to be used on various vessels (including small ones). And the constancy of the width of the radiation pattern in a wide frequency range and the absence of side lobes makes sonar systems with a parametric mode of operation an almost indispensable tool for studying shallow areas of the oceans.

Determining the amount of biological resources is an urgent and complex scientific and technical task from the point of view of ecological monitoring of the water. Traverse-scan parametric sonar is a promising tool that can significantly increase the productivity of searching and monitoring bioresources in shallow water.

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