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Role of the Speed of Sound's Dispersion in Improving the Efficiency of a Parametric Antenna in a Shallow Waveguide

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Abstract—The possibility is considered of increasing the efficiency of a parametric antenna when exciting acoustic modes in a shallow marine waveguide. It is shown that the complete compression of acoustic signals propagating in the shelf sea can be achieved with a corresponding increase in their intensity if a special mode of frequency modulation is selected. Results are presented from an experimental study of this effect in the propagation of a broadband acoustic signal of a parametric antenna in the shelf sea.

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INTRODUCTION

The development of new acoustic tools and techniques for studying the ocean on long tracks continues to be relevant. Accomplishing it requires means that are adaptive to the structure of the ocean. One of these is based on the principles of nonlinear acoustics using directional broadband parametric emission [1]. A parametric antenna is formed in a medium during the collinear interaction of intense sound waves (so-called pumping). Such an antenna is well known as a tool for profiling bottom structures. One feature of a parametric antenna is an extremely narrow beam pattern (usually several degrees of angular resolution) for low-frequency signals [2]. The effective width of the diagram remains constant over a wide range of frequencies. A parametric antenna differs from conventional antennas with comparable characteristics of the beam pattern at relatively small sizes, a wide frequency band of the emitted signal (two octaves or more), and a sharp directional characteristic throughout the range of frequencies. Experience in using a parametric antenna shows that it allows single-mode excitation of an underwater sound channel [3]. The expansion of the band of acoustic signals raises the spatial resolution of studies, improves the quality of information transmission and underwater communications, and allows the use of new approaches in hydrophysical research, especially in the acoustic tomography of marine waters via the frequency processing of signals propagating along a single track instead of the familiar spatial processing of signals propagating along different tracks [4, 5]. L.M. Brekhovskikh noted that the acoustic characteristics of a parametric antenna make it an "ideal tool for ocean acoustics" [6]. The low efficiency of parametric antennas hinders their widespread use in marine experiments. Conventional acoustic antennas have a fairly high value of acoustic emission power per unit of the exciting generator's electric power. However, the debate about the possibility of parametric antennas competing with traditional hydroacoustic tools began almost immediately after they appeared. Part of this debate was described in [7], where it was noted in particular that when the reverberation of the acoustic signal is substantial, the narrow beam and the absence of side lobes in the beam pattern can more than compensate for the low levels of the parametric antenna's emitting. It also indicates that a wider band can be used to improve the signal-to-noise ratio via broadband signal processing. Note too that the efficiency of a parametric antenna's emitting grows along with its power when sounding the ocean over long tracks. In this work, we consider the idea of increasing the signal-to-noise ratio via parametric emitting under conditions where the dispersion of a broadband acoustic signal propagating in an underwater waveguide results in its compression and the local concentration of its energy in a given area of the waveguide.

Ways of improving the efficiency of acoustic sounding in the ocean, especially in the shelf sea, are now a subject of active debate. One area of interest is focusing acoustic radiation in a marine waveguide [8, 9]. Scientists prefer to solve this problem by using wavefront reversal [10–12]. It is believed that the spatial focusing of acoustic emission in the waveguide's thickness would reduce the scattering at its boundaries and thereby increase the ratio between the useful signal and the noise caused by reverberation. Due to the highly directional nature of emission in a wide frequency band [13], a parametric antenna provides single-mode excitation of an underwater acoustic waveguide and is one device that allows implementation of these techniques.

The aim of this work is to discuss the capabilities of a hydroacoustic antenna, operating on principles of nonlinear acoustics, to concentrate the energy of an emitted acoustic signal in a given region of the waveguide's space during compression of a broadband signal due to waveguide dispersion. Results are presented from an experimental study of the propagation characteristics of broadband parametric emission in an underwater sound channel.

EXPERIMENTAL

One feature of a parametric antenna is an extremely narrow beam pattern (in our studies, the characteristic width of the pattern in the vertical plane was 6°) for low-frequency acoustic signals. The width of a parametric antenna's diagram is virtually constant over a wide frequency band and has no side lobes. It can therefore allow selective excitation of the modes of a broadband acoustic signal in a marine waveguide. The sound signal forms in the marine environment, which is excited by intense high-frequency acoustic pumping modulated in amplitude. As a result, a traveling wave antenna is formed in the waveguide, which generates sharply directed emission of the signal at the frequency of modulation. Such a low-frequency acoustic signal emitted in a parametric manner will then propagate independently of high-frequency pumping, which rapidly decays. A parametric antenna provides emission of sounding signals in a wide frequency band, due to the nonresonant way of generating a low-frequency signal.

Experimental studies were performed in August 2018 in the Taganrog Bay of the Sea of Azov. The emitting antenna was positioned on the bottom and equipped with a rotary device that allowed scanning of the water area with a narrow beam of parametric emission in a horizontal plane. The axis of emission was oriented horizontally.

The parametric antenna was in the form of a mosaic of radiating elements, half of which emitted a high-frequency pumping signal at one frequency. The other half emitted at another frequency slightly different in value. The mean frequency of emission (pump frequency) was 150 kHz. The difference frequency (the signal's frequency of emission) was in the range of 5–20 kHz. The electric power of the antenna amplifier was 1 kW for each pump frequency. The receiving antenna was in the form of a vertical chain of five hydrophones, mounted on a metal rod with a step of 0.3 m. This rod was a part of a rigid structure, positioned on the bottom so that the vertical chain of hydrophones overlapped almost the entire waveguide. Two more hydrophones were attached to the sides of the rod to determine the direction of the signals' arrival. The signal from the antenna's receiving elements was transmitted by cable to the receiving boat, where it was digitized and recorded for subsequent processing. The vertical distribution of the speed of sound's propagation in the waveguide varied considerably; it changed notably over time and with the place of measuring. Such a distribution ensured the near-bottom propagation of sound.

Measurements showed that the directionality of parametric emission remained virtually the same in the 5 to 15 kHz range of frequencies and was 10° at half the power of emission. Due to design features of the emitter, this directionality is even stronger in the vertical plane. The mode of pattern measurement, in which when the emitting antenna rotated slowly in the horizontal plane, was used because of the high directionality of the parametric antenna's emittance. The maximum intensity of the received signals was determined on a stationary vertical chain of receivers positioned on the bottom, and pulses of frequency-modulated signals were then emitted. The duration of the emission pulses varied from 0.7 to 3 ms, and the interval between pulses was around 300 ms. Signals were recorded in parallel from each receiver of the vertical antenna. The measurements were made at distances of 0.5 to 1.5 km between the emitter and the receiving antenna. The signal decayed quickly at great distances as a result of the near-bottom propagation of sound.

RESULTS AND DISCUSSION

We studied the temporal–frequency characteristics of the propagation of pulses whose frequency of filling varied in the range of 7–15 kHz. The frequency evolution of a signal proceeded from the lower to the upper frequencies. This corresponded to the normal waveguide dispersion, where the group speed of a signal's propagation grows along with frequency. Analysis of our results showed this was the best range of frequencies for this experiment. Even though the waveguide dispersion rose as the frequency fell, the parametric antenna's efficiency of emission diminished. The efficiency of parametric radiation grew along with frequency, but dispersion declined rapidly. The waveguide dispersion was acceptable in our range of frequencies, and the intensity of the parametric signal at distances of 1000 and 1500 m changed little throughout the range of frequencies. Figure 1 shows the oscillograms of acoustic chirp pulses 3 ms in duration, recorded by the receiving antenna's hydrophones at a distance of 1000 m. It can be seen that field of para-

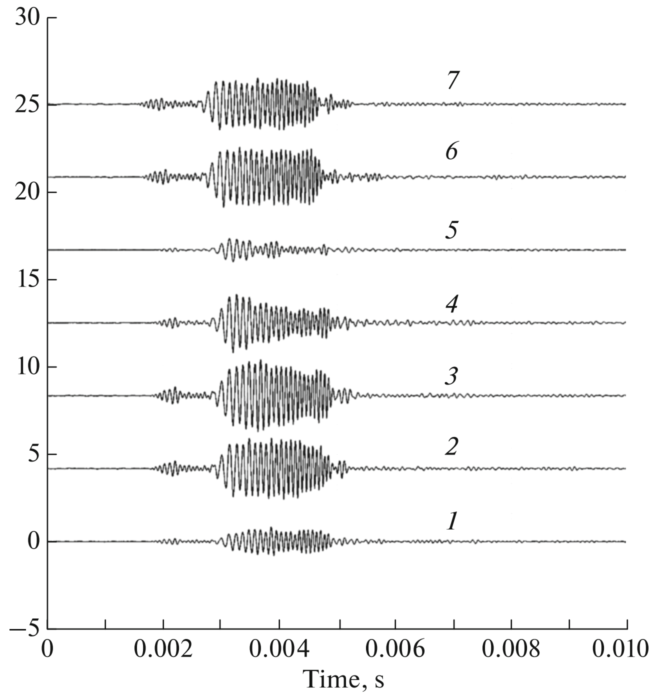

Fig. 1. Oscillograms of the signals recorded by the hydrophones of the receiving antenna. The numbers correspond to the ordinal number of the hydrophone, according to the distance from the bottom. The maximum signal level was recorded by hydrophones (*2*) and (*3*), which corresponds to bottom propagation. Hydrophones (*6*) and (*7*) were installed at the level of hydrophone (*2*) and measured the direction of signal arrival.

metric emission was concentrated in the middle part of the waveguide, and the signals recorded by different hydrophones of the receiving antenna were in phase over the depth of the waveguide, corresponding to its first mode of excitation.

The oscillograms show typical features associated with the propagation of a pulse of parametric emission in a waveguide. We can distinguish the chirp signal itself and its precursor associated with the excitation of the second harmonic of the main signal (Fig. 2). The registered duration of the chirp signal was 2 ms, while that of the emitted pulse was 3 ms. The duration of the broadband signal was reduced by 1 ms when propagating in the waveguide at a distance of 1000 m. These features were noted earlier in studying the waveguide propagation of a parametric antenna signal [2].

Based on our analysis of the frequency dispersion of the speed of waveguide sound propagation under these conditions, we would expect complete compression of the parametric signal in the selected frequency band at an emission duration of 1.7 ms and a distance of 1500 m. Note that these distances fully correspond to the distant propagation of a signal. In our experiments, the range of propagation exceeded the scale of the vertical waveguide by 500–750 times. The effect of a broadband parametric signal's compression is shown in Fig. 3. Because of attenuation, the signal precursor is less notable than at a distance of 1000 m. The signal itself, with a duration of 1.7 ms propagating in a shallow waveguide (depth along the path, 2 m), is compressed at 1500 m into a pulse with a duration of 0.4 ms. Reflections from the boat next to the receiving antenna are visible behind this pulse. The duration of the signal was compressed by more than four times.

FEATURES OF THE WAVEGUIDE PROPAGATION OF DIRECTIONAL BROADBAND EMISSION

Maximum compression τ of a signal is determined by the effective frequency band of its spectrum Δf, $\tau = (\Delta f)^{-1}$. On the other hand, duration T of an emitted pulse, provided it is completely compressed at distance L, is determined by frequency dispersion $\partial c/\partial f$ of speed c of sound wave propagation:

$$T = L\frac{\partial c/\partial f}{c^2}\Delta f. \quad (1)$$

When a signal is compressed as a result of waveguide dispersion, we can therefore increase its intensity by a factor of T/τ:

$$T/\tau = L\frac{\partial c/\partial f}{c^2}\Delta f^2. \quad (2)$$

In other words, the effect of increasing the intensity is proportional to the distance over which the signal extends, the magnitude of waveguide dispersion, and the square of the signal's frequency band. This increases the ratio between the signal and the noise that accumulates in the recording equipment when receiving signal τ.

Note that the group speed of a signal's propagation in a waveguide is determined by the latter's parameters. When using a Pekeris waveguide with constant speed c_0 of sound propagation that is independent of depth, the frequency dependence of the speed of signal propagation is determined by the relation

$$c = c_0\left[1 - \frac{c_0^2 l^2}{(2fH)^2}\right]^{1/2}, \quad (3)$$

where H is the vertical scale of the waveguide, and l is the mode number. We thus obtain the limit estimate of the frequency dispersion of the speed of sound in the waveguide: $\partial c/\partial f \approx f^{-2}$. When a signal with constant relative frequency band $\Delta f/f$ = const is emitted, the relative compression of signal T/τ grows along with distance L of signal propagation and diminishing waveguide thickness. The strongest effect of a relative increase in the intensity of a broadband signal can thus

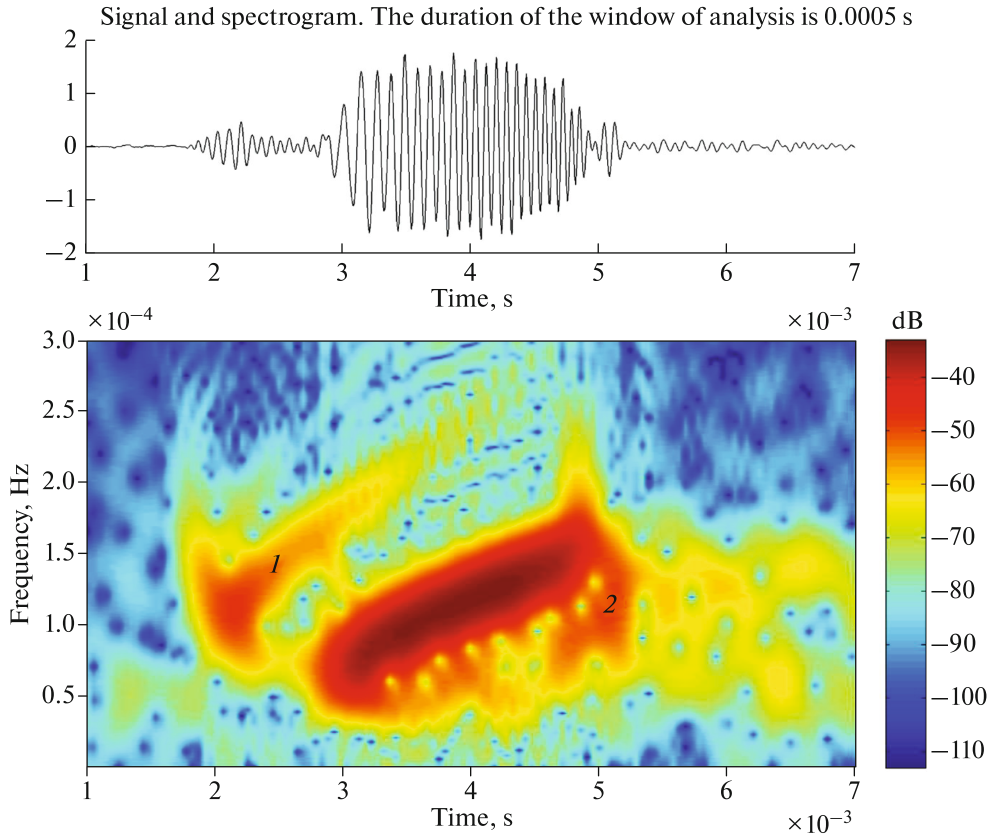

Fig. 2. Spectrogram of a chirp signal with duration of 3 ms, recorded by hydrophone (*2*) at a distance of 1000 km. (*1*) Precursor; (*2*) reflection from the boat. The level of the signal is given in arbitrary units.

be obtained with long-track waveguide propagation in the shelf sea.

The duration of a frequency-modulated signal as it propagates in a waveguide thus shortens with distance: $T(r) = T_0 - \Delta T$, where T_0 is the initial duration of the signal, associated (according to expression (1)) with frequency dispersion $\partial c/\partial f$ in the waveguide and distance L at which the maximum compression of the signal is achieved:

$$\Delta T = rc^{-2}\frac{\partial c}{\partial f}\Delta f, \tag{4}$$

where r is the distance covered by the signal. Using the law of conservation of energy, we then obtain an expression for the intensity of the signal as it propagates in the waveguide. Since the accuracy of determining signal duration $\tau = \Delta f^{-1}$ is related to its frequency band Δf, we have

$$I(r) = I_0(R/r)\left(\frac{T_0}{T+\tau}\right) = I_0\frac{R}{L}\frac{L}{r(1 - r/L + \tau/T_0)}, \tag{5}$$

where R is the spatial scale characteristic of waveguide propagation; L is the distance of the maximum compression of the signal; and I_0 is the initial intensity of the signal at the input to the waveguide.

With broadband signal $\tau/T_0 \ll 1$, relative intensity $I(r)/I_0$ reaches a maximum at $r = L$. The maximum of ratio $I(r)/I_0$ depends on the dispersion properties of the waveguide and the square of the frequency band of the signal. According to expressions (1)–(3), this ratio is

$$\left.\frac{I_{max}}{I_0}\right|_{r=L} = rc^{-2}\frac{\partial c}{\partial f}\Delta f^2. \tag{6}$$

Ratio I_{max}/I_0 grows rapidly along with the frequency band of the signal and can be as high as 1 : 1 (or even more) at the octave band of the signal.

Figure 4 shows the relative change in the intensity of a frequency-modulated signal, compared to typical examples of spherical signal propagation in a homogeneous medium or cylindrical propagation in an ideal waveguide. It is seen that the intensity of the frequency-modulated signal reaches a maximum, forming an acoustic barrier at which the maximum ratio between the intensity of the parametric antenna's signal and the noise of the water area is reached. The effi-

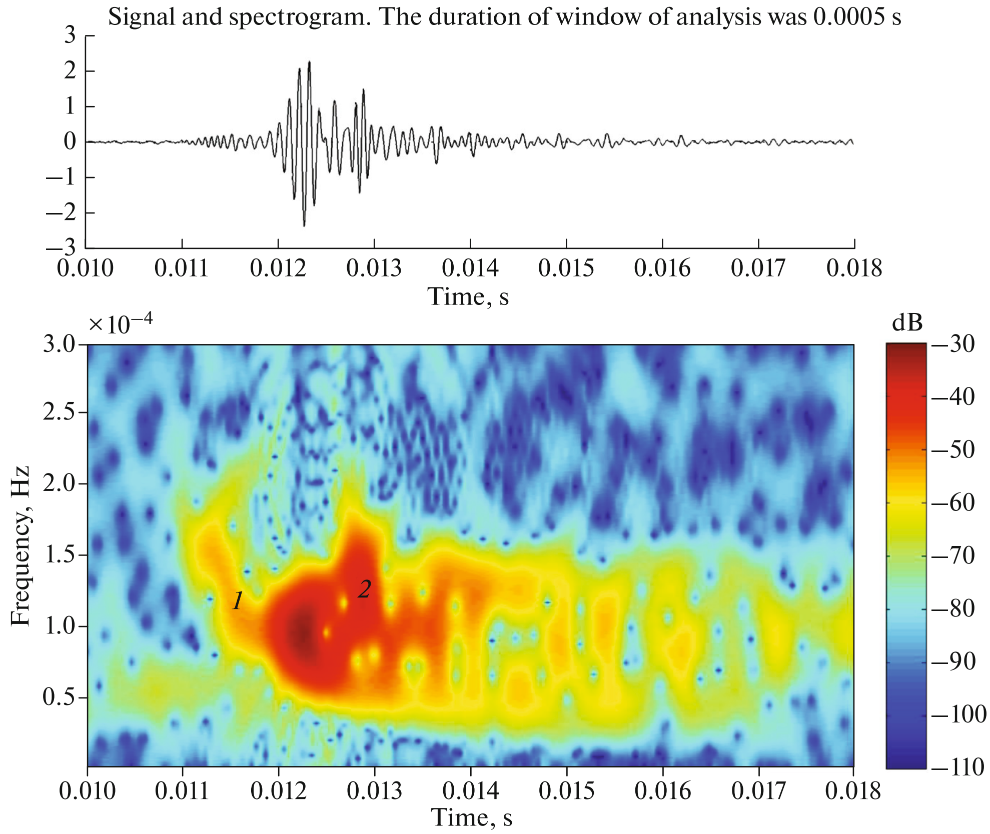

Fig. 3. Spectrogram of the compression of a signal with duration of 1.7 ms, recorded by hydrophone *2* at a distance of 1500 m. (*1*) Precursor; (*2*) reflection from the boat. The level of the signal is given in arbitrary units.

ciency of the parametric antenna reaches its maximum in this area. The intensity of the signal falls rapidly after this barrier, since its duration begins to grow rapidly as a result of frequency dispersion.

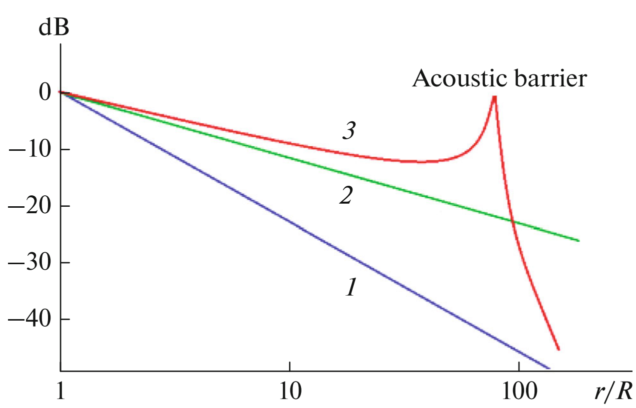

Fig. 4. Dependence of the intensity of an acoustic signal on distance r/R. (*1*) Homogeneous medium $I/I_0(R/r)^2$; (*2*) ideal waveguide $I/I_0(R/r)$; (*3*) frequency-modulated signal in the waveguide (expression (5)). R is the spatial scale of the acoustic field.

CONCLUSIONS

The conditions of propagation in a shallow waveguide corresponded in our case to normal waveguide dispersion, where the group speed of signal propagation grows with frequency. To achieve the effect of a broadband signal's compression as it propagates in the waveguide, we must therefore increase its frequency during signal emission. Such modulation was used in our experiments.

Calculating the group speed of dispersion allows us to estimate the variation in the delay of a signal's different frequency components as it propagates in the waveguide. The temporal–frequency relationships in the signal change as the distance grows. The delay in the low-frequency components of the signal increases; as a result, the difference between the time of arrival of the beginning and end of the parametric signal is reduced. This corresponds to a shortening of its duration, and the signal is compressed. Analysis shows that the condition for the simultaneous arrival of low-frequency and high-frequency components is determined by both the duration of the emission and the distance at which such signal compression proceeds. Experience shows that special frequency modulation corresponding to the characteristics of dispersion in the waveguide is required to achieve complete synchronism of the time at which all frequency components of the signal arrive. Since the dispersion of the speed of signal propagation depends nonlinearly on the frequency, the frequency modulation must be nonlinear in nature so as to achieve maximum signal compression.

Our experiments demonstrated the possibility of compressing a broadband acoustic pulse as a result of the action of waveguide dispersion as it propagates in a shelf sea. A parametric antenna was used to emit broadband signals. Due to its high directionality and nonresonant signal generation, the parametric antenna allowed single-mode excitation of the waveguide in a wide band of frequencies. The relative width of the signal's frequency band can in this case be as great as an octave (or more).

The frequency modulation of the signal used in our experiments did not fully correspond to the nature of the waveguide dispersion of the speed of sound detected experimentally. Compensating for the durations of propagation of a signal's different frequency components was possible only in a limited range of frequencies. This ensured signal compression of more than four times at a distance of 1.5 km. Special frequency modulation corresponding to the characteristics of the dispersion of the speed of sound in a waveguide is required to completely synchronize the arrival of all frequency components of the signal. Calculations showed it is then possible to compress the signal by ten times under experimental conditions.

Analysis showed that the compression of the signal as a result of waveguide dispersion is proportional to its range for given dispersion values and the relative width of the signal frequency band. Compression of the signal increases its intensity. When the frequency characteristics of the signal are matched with the characteristics of waveguide dispersion along its track of propagation, the increase in its intensity can accurately compensate for the drop in signal intensity with distance when the mode of propagation is cylindrical in a layered waveguide. This conclusion can be considered only qualitatively, since our analysis assumed propagation of the signal in an ideal homogeneous waveguide without losses. Attenuation of the signal as it propagated in a shallow waveguide limited the distance at which the effect of signal compression was observed.

The most efficient compression of broadband signals is possible on fairly long tracks with single-mode excitation of the waveguide. The compression of the broadband signal considered here was a purely linear acoustic procedure. However, a parametric antenna operating on the principles of nonlinear acoustics is the most effective tool for studying the compression of acoustic signals in marine waveguides, due to its characteristics with respect to the selective excitation of modes in the waveguide in a wide range of frequencies.

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REFERENCES

1. Esipov, I.B., Popov, O.E., Kenigsberger, G.V., and Sizov, I.I., *Bull. Russ. Acad. Sci.: Phys.*, 2016, vol. 80, no. 10, p. 1209.
2. Novikov, B.K., Rudenko, O.V., and Timoshenko, V.I., *Nelineinaya gidroakustika* (Nonlinear Hydroacoustics), Leningrad: Sudostroenie, 1981.
3. Esipov, I.B., Popov, O.E., Voronin, V.A., and Tarasov, S.P., *Acoust. Phys.*, 2009, vol. 55, no. 1, p. 76.
4. Charnotskiĭ, M.I., Fuks, M., Naugol'nykh, K.A., et al., *Acoust. Phys.*, 2006, vol. 52, no. 2, p. 222.
5. Esipov, I.B., Chernousov, A.D., and Popov, O.E., *Bull. Russ. Acad. Sci.: Phys.*, 2018, vol. 82, no. 5, p. 470.
6. Brekhovskikh, L.M., *Okean i chelovek: Nastoyashchee i budushchee* (Ocean and People: Present and Future), Moscow: Nauka, 1987.
7. Muir, T.G. and Goldsberry, T.G., *Proc. of the NATO Adv. Study Inst.*, Copenhagen: Leif Bjorno, 1980, p. 187.
8. Kuz'kin, V.M. and Pereselkov, S.A., *Acoust. Phys.*, 2006, vol. 52, no. 5, p. 598.
9. Grigor'ev, V.A. and Kuz'kin, V.M., *Acoust. Phys.*, 2005, vol. 51, no. 3, p. 292.
10. Kim, S., Kuperman, W.A., Hodgkiss, W.S., et al., *J. Acoust. Soc. Am.*, 2004, vol. 115, no. 4, p. 1525.
11. Zverev, V.A., *Acoust. Phys.*, 2004, vol. 50, no. 6, p. 685.
12. Kuperman, W.A., Hodgkiss, W.S., Song, H.C., et al., *J. Acoust. Soc. Am.*, 1998, vol. 103, no. 1, p. 25.
13. Esipov, I.B., Popov, O.E., and Soldatov, G.V., *Acoust. Phys.*, vol. 65, no. 4, p. 2019.
14. Brekhovskikh, L.M. and Lysanov, Yu.P., *Teoreticheskie osnovy akustiki okeana* (Theoretical Foundations of Ocean Acoustics), Leningrad: Gidrometeoizdat, 1982.

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