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OCEANOLOGY

Acoustical Nonlinearity, Sound Absorption, and Scattering in Bubble-Saturated Seawater

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Abstract—A correlation between acoustical nonlinearity, sound absorption, and scattering in a subsurface bubble-saturated layer is established. A model of effective parameters of a bubbly liquid is developed that allows one to obtain results coinciding with experimental field studies. It is shown that "bubbly clouds" under the sea surface increase substantially the sound scattering and the nonlinear acoustic parameter of the seawater.

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The subsurface sea layer under a rising sea is characterized by anomalously high concentrations of gas bubbles, which lead to increased sound scattering and absorption and to growing nonlinear characteristics of this layer, i.e., to a sharp increase in the acoustical nonlinearity [1, 2]. Measurements of the bubble concentration and their size distribution $g(R)$ in the sea have been carried out by various methods (mainly optical and acoustical), and the results have been presented in many studies [4–9]. Based on summary of works devoted to measurements of the bubble concentration and their size distribution in a subsurface sea layer, the model of bubble size distribution g(R) was proposed. An advantage of this model is the usability and the rate of calculations of different parameters of a microinhomogeneous medium [11]. The goal of our work is to study the correlations between linear and nonlinear parameters of the bubble-saturated seawater in the subsurface sea layer based on experimental results and using model functions $g(R)$.

Experimental studies were carried out in Vityaz Bay of the Sea of Japan at the marine field unit of the Il'ichev Pacific Oceanological Institute, Far East Branch, Russian Academy of Sciences (POI FEB RAS), about 100 km south of Vladivostok and at the research unit "Impuls" of POI FEB RAS along various paths in the water area of Peter the Great Gulf of the Sea of Japan in the summer and autumn seasons of 2010–2016. In Vityaz Bay a bottom system with hydroacoustic broadband spot-beam radiating and receiving antennas was mounted at a depth of 12 m for long-term study of the acoustic characteristics of the sea under various hydrometeorological conditions [12, 13]. Measurements of the nonlinear characteristics of the sound field were carried out using parametric sound radiators [13].

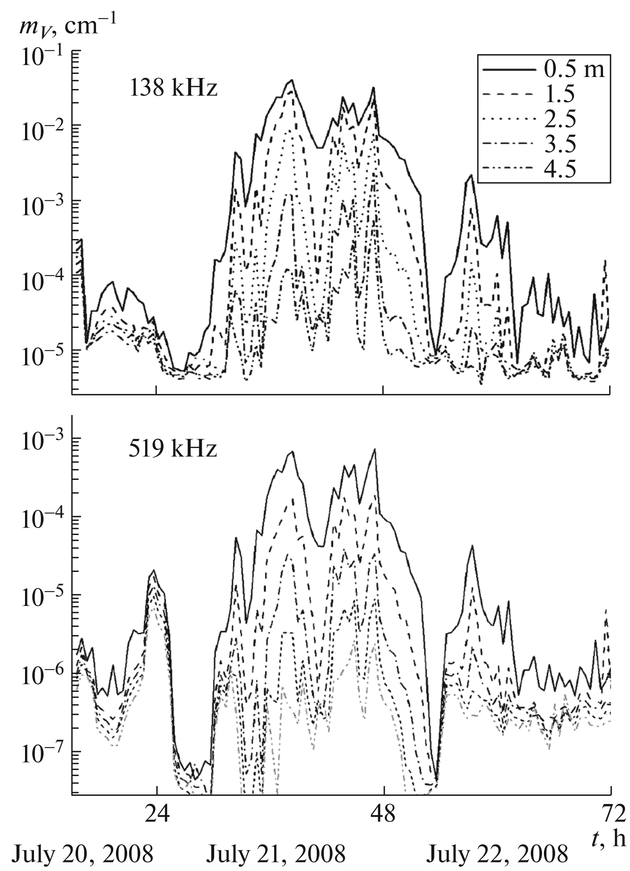

Fig. 1. Variations in the volume sound scattering coefficient in the subsurface sea layer at depths of 0.5, 1.5, 2.5, 3.5, and 4.5 m obtained at the frequencies of 138 and 519 kHz over two days with variations of the wind speed from 1–2 to 14 m/s.

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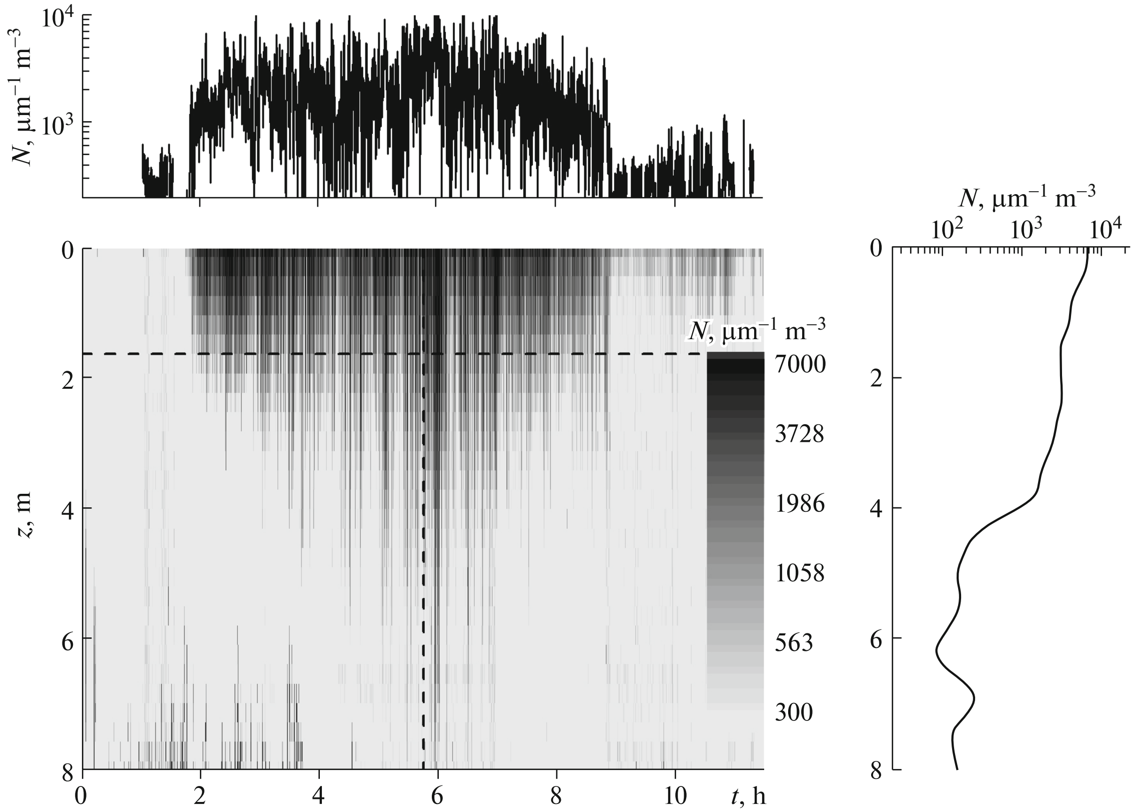

Fig. 2. Depth distribution of bubbles and its variation over 11.5 h due to changes in the wind speed and sea disturbance. At the top is the temporal dependence of the concentration N of bubbles with a size of 20 μm at a depth of 1.8 m; on the right is the vertical cross section $N(z)$ at the instant 5:40 h at maximal entrainment of bubbles into the sea column.

To describe the sound scattering, volume scattering coefficient m_V is used; it is defined in the Born approximation as [1, 3, 5]

$$m_V = \frac{2}{\pi\theta^2 c\tau}\left(\frac{P_{bs}}{P_i}\right)^2, \quad (1)$$

where P_i and P_{bs} are the amplitudes of a wave falling onto scattering volume V and the backscattered wave; for pencil emitters, θ is the width of the directivity pattern, c is the sound velocity, and τ is the duration of the acoustic pulse.

Figure 1 shows a typical volume sound scattering coefficient obtained at different frequencies in the subsurface sea layer over two days with substantially varying wind speed from 1–2 m/s to 14 m/s. It can be seen from Fig. 1 that a strong sound scattering near the surface was observed after about one day due to bubbles entrained at a depth up to 6–10 m. Here, the value of m_V increased by 30–40 dB. The bubble size distribution $g(R)$ can be found from the frequency dependence of sound scattering coefficient $m_V(\omega)$ assuming that the main contribution to scattering is made by resonance bubbles. For that relation $R(\omega)$ between the radius and the resonance frequency is described by the Minnert formula [3, 5]:

$$g(R(\omega)) = \frac{2\delta_\omega}{\pi R^3(\omega)} m_V(\omega), \qquad R(\omega) = \frac{\sqrt{3\gamma P_0/\rho}}{\omega}, \quad (2)$$

where δ_ω is the resonance attenuation coefficient at frequency ω, P_0 is the hydrostatic pressure, and $\gamma \approx 1.4$ is the adiabatic index of the gas within a bubble. Often, instead of the value of $g(R)$ [cm^{-4}], the value of $N(R)$ [m^{-3} μm^{-1}] is used (especially in English-language publications), which is related to $g(R)$ as [1, 3, 5–9]

$$N(R)\ [\text{m}^{-3}\ \mu\text{m}^{-1}] = 10^2 g(R)\ [\text{cm}^{-4}]. \quad (3)$$

Figure 2 shows the value of $N(R)$ for the resonance bubbles at a given frequency 138 kHz at various depths and at various times during evolution of a surface disturbance under various sea conditions: before the start, during, and after cessation of the wind.

It is known that bubbles are effective absorbers of the energy of sound waves propagating in the sea. Let us estimate the sound absorption coefficient using the formula [3, 5, 8, 9, 11]

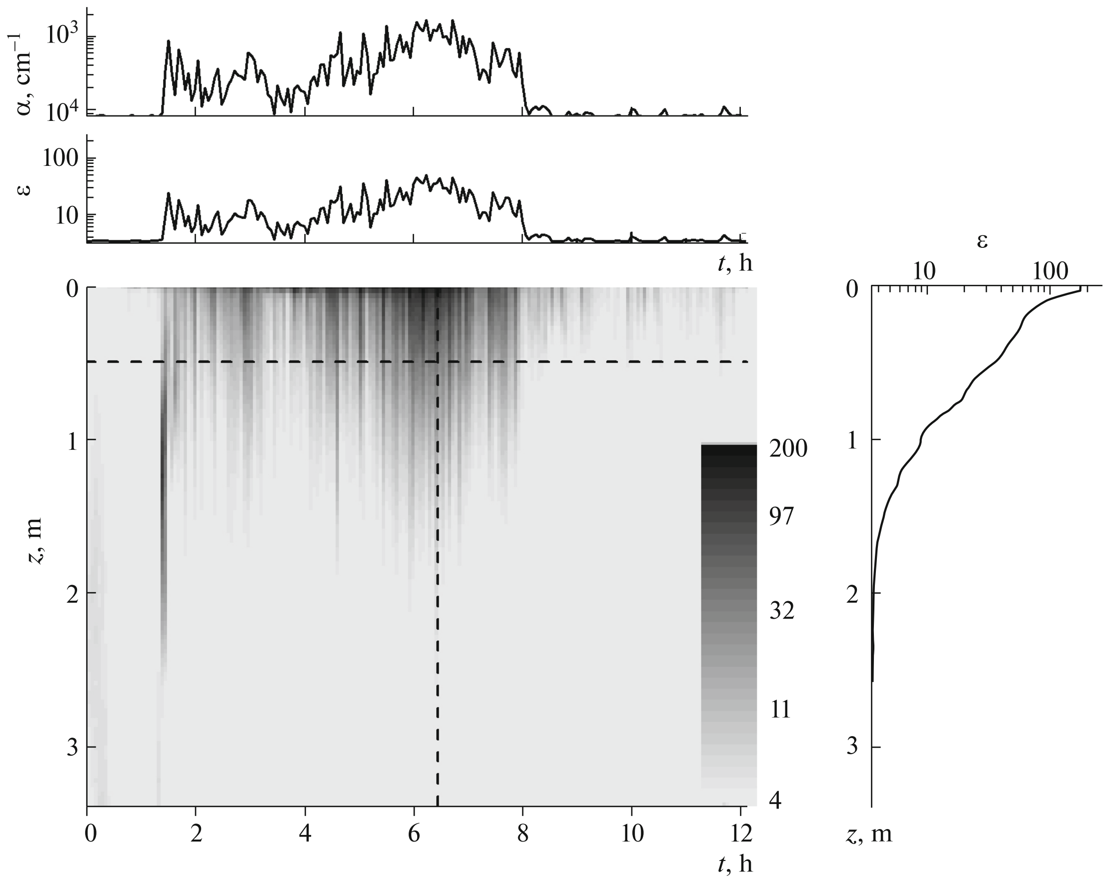

Fig. 3. Depth distribution of the acoustical nonlinearity ε and its variation over 12 hours due to entrainment of bubbles into the seawater under changes in the wind speed and sea disturbance. Pictures at the top show the correlation between the acoustical nonlinearity ε and the sound absorption α at the depth of 0.5 m marked by a horizontal dashed line in the lower picture; on the right is the vertical cross section ε(z) at the instant 6:25 h at maximal entrainment of bubbles in the sea column.

$$\alpha \approx \frac{\omega}{c}\mathrm{Im}\left[1+\frac{4\pi}{3}\frac{\rho c^2}{\gamma P_0}\int_0^\infty \frac{g(R)dR}{1-(R/R_\omega)^2(1+i\delta_\omega)}\right]^{1/2}, \quad (4)$$

where previously obtained approximations for $g(R)$ were used in the form

$$g(R) = A_g R^{-n}\exp\left[-n\left(\frac{R_p}{R}-1\right)-\frac{R}{R_m}\right]. \quad (5)$$

In (5), exponent n and critical sizes R_p and R_m are the natural parameters following from the Garrett–Farmer theory [1]. In addition, it turns out that the value $n \sim 3.3$, although measurements of $g(R)$ using a significant factual material for a moderate sea yield $n \sim 3.5$–3.8 [5–10]. The value of the sound absorption can be calculated using the experimental data obtained for the sound scattering with bubbly structures beneath the sea surface. Figure 2 presents such calculations for the depth of 0.3 m, which indicates extra sound absorption in the bubbly layer; beneath the sea surface, the sound absorption is 100 times higher than that in pure water $\alpha_0 = 0.008\ \mathrm{m}^{-1}$.

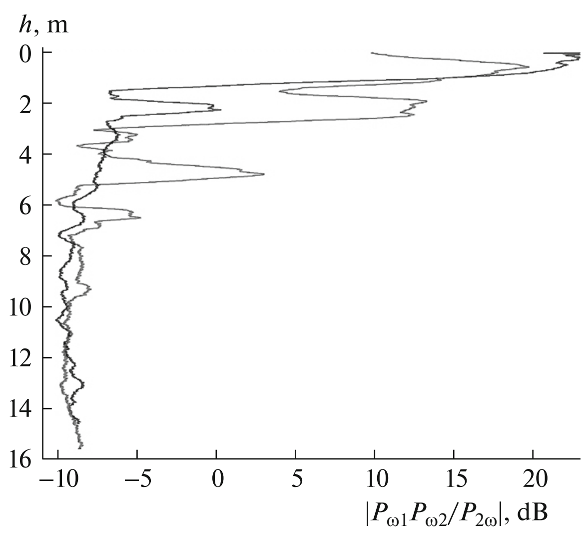

Fig. 4. Depth distribution of the acoustic signal at the second harmonic generated in the beam crossing region (two soundings at 10 min interval).

An important parameter in nonlinear hydroacoustics is acoustical nonlinear parameter ε. At high sound amplitudes, it defines discontinuity distance r^* as $r^* = 1/\varepsilon k\mathrm{M}$ [14], where $k = \omega/c$ is the wave number, $\mathrm{M} = v/c = P/\rho c^2$ is the Mach number, and v and P are the particle velocity and pressure in a wave, respectively.

Parameter ε in a microinhomogeneous sea medium depends on the medium structure along with the dynamic properties of inclusions [14]. The value of ε is defined as

$$\frac{\varepsilon_e}{\varepsilon} \approx \left[1 + \frac{\beta'}{\beta}\int_0^\infty \frac{R^3 g(R)dR}{q(R,R_\omega)}\right]^{-2} \left\{1 + \frac{4\pi}{3}\frac{\beta'^2\varepsilon'}{\beta^2\varepsilon}\right. \\ \left.\times \int_0^\infty dRR^3 g(R)\left[1 + \frac{2\varepsilon' - 1}{\varepsilon'}\left(1 - \frac{(R/R_\omega)^2}{(q(R,R_\omega))^2}\right)\right]\right\}, \tag{6}$$

$$q(R,R_\omega) = 1 - (R/R_\omega)^2(1 + i\delta). \tag{7}$$

The results obtained above on the bubble concentration in the subsurface layers of seawater allow defining an additional acoustical nonlinearity introduced by distributed bubbles with high nonlinearity. Figure 3 shows the temporal dependences of the nonlinear parameter of the bubbly layer relevant to that presented in Fig. 2 for the bubble concentration. Beneath the sea surface, the nonlinear parameter exceeds substantially that for pure water, which is equal to 3.5. At great depths the nonlinear parameter tends to that for pure water.

Experimental studies of the nonlinear parameter distribution in seawater were carried out using a sounding setup based on an acoustic antenna, radiators of which are mounted at an angle of the beam crossing in a region of nonlinear interaction with microinhomogeneities of the sea medium [13].

Figure 4 shows the depth distribution of the acoustic signal at the second harmonic $\left|\frac{P_{2\omega}}{P_{\omega_1}P_{\omega_2}}\right|$ generated in the beam crossing region. Here, normalization by the radiated signal power at a pump of 57 and 63 kHz was carried out. It can be seen from Fig. 4 that in the subsurface layer to a depth of 5–8 m a considerable variability of the value $\left|\frac{P_{2\omega}}{P_{\omega_1}P_{\omega_2}}\right|$ is observed reaching 30 dB over the background value. Such a considerable excess confirms a considerable increase in the nonlinearity in the subsurface layer to the depth of 5–8 m, which agrees with the results presented in Fig. 3.

Thus, in the present work, simulation of the acoustic characteristics of the subsurface sea layer is implemented using model functions $g(R)$ based on experimental studies of the sound scattering and the size distribution of bubbles. Correlations between the linear and nonlinear acoustical characteristics of the bubble-saturated seawater in the subsurface sea layer are established. It is shown that the data on the sound scattering allows one to estimate the bubble concentration, the sound absorption and the acoustical nonlinearity of the bubbly seawater, and a whole number of bubbles in a size range. Measurements carried out of the seawater nonlinearity in situ have demonstrated coincidence of experimentally measured values with theoretical estimates based on the computational method using the data on sound scattering by bubbles in the sea subsurface layers.

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