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OCEANOLOGY

Features of Sound Propagation in the Presence of Bubble Clouds in the Perturbed Surface Layer of the Ocean

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Abstract—There are contradictory opinions on the contribution of the near-surface layer of bubbles to the attenuation of low-frequency sound in the ocean. Taking into account the new experimental data on the distribution of bubbles in seawater, it is shown that the influence of the near-surface layer of bubbles on the structure of the spatial decay in sound propagation can be significant at rather typical concentrations of bubbles in the near-surface layers of the ocean. A possible explanation for the contradictions is the spatial restructuring of the field in which the main effect of the bubbles is focused on the near distance; sound attenuation at a great distance is not affected.

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Entrainment of bubbles in the seawater column by the motion dynamics in surface waves leads to the formation of bubble clouds [1, 2], which can reach great depths of tens of meters during a strong wind. The bubbles exert a significant effect on the acoustic properties of water, causing, among other things, excessive absorption and scattering of sound [2, 3]. There exist contradictory opinions on the contribution of the near-surface layer of bubbles to the attenuation of low-frequency sound in the ocean [5–12]. A conclusion was stated in [4] that a layer of bubbles weakly affects sound attenuation in the sea up to high wind velocities. It was shown in [5, 6] that the contribution of the bubbles to sound attenuation at frequencies from 1 to 8 kHz in a shallow sea is dominant. On the other hand, it is suggested in [7] that the bubbles affect the sound attenuation insignificantly. In [8, 9] the problem on sound propagation was further pursued. The effect of the bubbles on the structure of the field in the sea is analyzed below based on new experimental results for the function of bubble distribution by sizes $g(R)$ obtained in [1, 2, 10].

We will take acoustic models of a microinhomogenous liquid, which make it possible to predict the major acoustic characteristics (sound velocity c, absorption, sound scattering, compressibility), as the basis [2, 3]. The coefficient of sound absorption α and the effective sound velocity c_e in the liquid with bubbles at different frequencies ω can be estimated by the approximate formulas:

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

$$\frac{c_e}{c} = \mathrm{Re}\left[\left(1+\frac{4\pi}{3}\frac{\rho c^2}{\gamma P_0}\int_0^\infty \frac{g(R)dR}{q(R,R_\omega)}\right)(1-x)\right]^{-1/2}, \quad x = \frac{4\pi}{3}\int_0^\infty R^3 g(R)dR, \quad (2)$$

where $q(R, R_\omega) = 1-(R/R_\omega)^2(1+i/Q_\omega)$, $R_\omega = \sqrt{3\gamma P_0/\rho}/\omega$, Q_ω is the quality factor of a bubble of radius R_ω, $\gamma = 1.4$ is the adiabat constant, ρ is the liquid density, β and β' are the adiabatic compressibility of the liquid ($\beta = 1/\rho c^2$) and gas in bubbles ($\beta' = \gamma/P_0$), and P_0 is the hydrostatic pressure in the liquid. Formulas (1) and (2) include function $g(R)$, which has the form [2, 3] $g = A_g R^{-n}\exp\{-n[(R_p/R)+(R/R_m)]\}$.

Figure 1 presents the frequency dependence of the coefficient of sound absorption α in water with bubbles at $T = 20°C$ calculated for a polydisperse mixture of bubbles of different concentrations x by formula (1). It also shows the frequency dependence of the coefficient of sound absorption in seawater $\alpha_{sea}(f)$ and freshwater $\alpha_0(f)$ at $T = 20°C$ and a salinity of 35 permille. The results presented can be used to estimate

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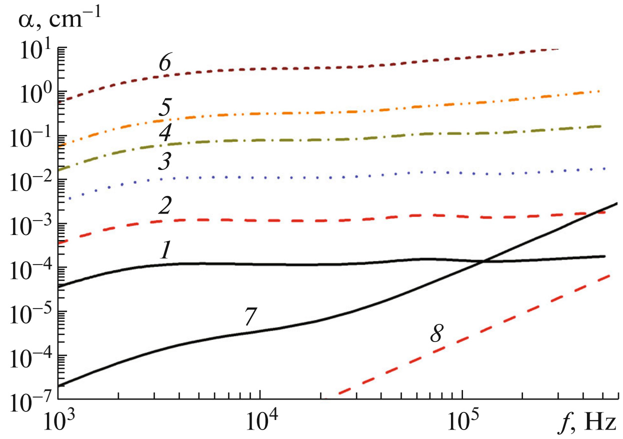

Fig. 1. Frequency dependence of the coefficient of sound absorption $\alpha(f)$ in water with a polydisperse mixture of bubbles at different concentrations of x: *1*, at $x = 10^{-8}$; *2*, at $x = 10^{-7}$; *3*, at $x = 10^{-6}$; *4*, at $x = 10^{-5}$; *5*, at $x = 10^{-4}$; *6*, at $x = 10^{-2}$; *7*, at $x = 0$, seawater; and *8*, at $x = 0$, freshwater.

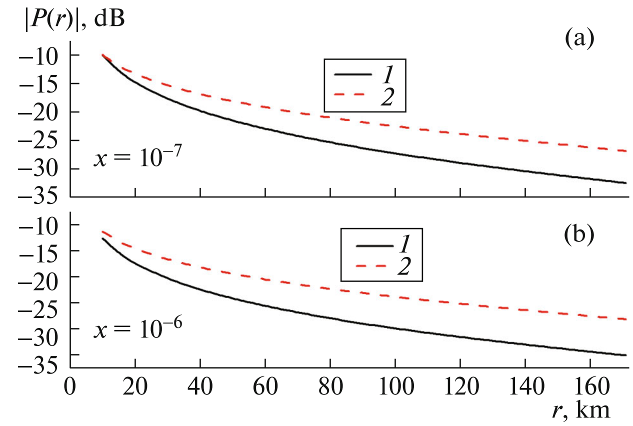

Fig. 2. Spatial decay of the acoustic field in the presence (curve *1*) and in the absence (curve *2*) of a near-surface layer of bubbles at a frequency of 800 Hz at different concentrations of bubbles: (a) $x = 10^{-7}$ and (b) 10^{-6}.

the contribution of the dissipative layer of bubbles to sound propagation in the sea.

We consider a model of a linear underwater sound channel with a near-surface layer of bubbles. We examine a model of a sound channel with a linear dependence of the sound velocity on depth in the form $c(z) = c_0(1 + az)$, where $a \approx 10^{-5}$ m^{-1} [11]. The rays emerging from the source at different angles approach the surface, where they are incident on the region of strong attenuation related to the presence of bubbles. Denote the coefficient of sound attenuation in the homogeneous liquid with bubbles by α_b and the distance along the horizontal at which the sound propagates and remains in the layer with thickness h by Δr_0. After N ray cycles, the losses for attenuation in the near-surface layer equal $A_b = \alpha_b \Delta r_0 N$, where $\Delta r_0 = 2h/\chi_0$, χ_0 is the angle of ray slip on the surface. Introducing the ray cycle duration $D(\chi_0)$, we determine the quantity of ray cycles at the distance r in the form $N = r/D(\chi_0)$. Taking into account that $D(\chi_0) = 2\tan(\chi_0)/a \approx 2\chi_0/a$, we obtain $A_b = \alpha_b(ah/\chi_0^2)r \equiv \alpha_{b\chi} r$. The attenuation A_b decreases upon an increase in the angle χ_0, and at a certain limit value $\chi_* = \sqrt{\alpha_b ah/\alpha_0}$, it becomes equal to attenuation in a pure liquid.

We consider the averaged decay law for a coherent field in the presence of a near-surface layer of bubbles. According to [11], the dependence of the mean square pressure is calculated by the formula

$$|P|^2 = \frac{2}{r}\left(\frac{c_1}{c}\right)^2 e^{-\alpha_0 r} \int_{q_1}^{q_H} \frac{e^{-\alpha r} \sin 2\chi_0 d\chi_0}{D(\chi_0)\sin\chi \sin\chi_1}, \quad (3)$$

where χ, χ_1, χ_0 are related by Snell's law $\cos\chi/c = \cos\chi_1/c_1 = \cos\chi_0/c_0$, the velocities c, c_1, c_0 correspond to the sound velocities on the horizons of the receiver z, the emitter z_1, and near the surface $z_0 = 0$, respectively. The values of q_1, q_2, q_H are estimated by the relationships $q_1 = \sqrt{2az_{\max}}$, $q_2 = \sqrt{2az_{\min}}$, $q_H = \sqrt{2aH}$, $z_{\max} = \max(z, z_1)$, and $z_{\min} = \min(z, z_1)$. Taking into account the smallness of the angles of slip, we obtain

$$|P(r)|^2 = \frac{4a}{r}\left(\frac{c_1}{c_0}\right)^2 \times e^{-\alpha_0 r} \begin{cases} 1/q_1, & r \ll r_1 = q_1^2/\alpha_b ah \\ \sqrt{\pi}/(2\chi_* \sqrt{\alpha_0 r}), & r_1 \ll r \ll 1/\alpha_0 \\ \dfrac{1}{\chi_*}\left(1 + \dfrac{\exp(-\alpha_0 r)}{2\alpha_0 r \chi_*}\right), & r \gg 1/\alpha_0 \end{cases} \quad (4)$$

from (3). Formula (4) shows that at great distances $r \gg 1/\alpha_0$ the value of $|P(r)|$ asymptotically approaches the cylindrical law of decay of the field $|P(r)| \sim 1/\sqrt{r}$ with the coefficient of sound attenuation equal to that in a medium without bubbles.

The dependences indicated are illustrated in Fig. 2, which depicts the function $|P(r)|$ when sound of different frequencies is emitted at a depth of 100 m in the sea without bubbles and in the presence of a near-surface layer of bubbles. The effect of the bubble layer consists in additional decay of the field at moderate distances, which is caused by attenuation of the sound that propagates at small angles of slip. All the energy concentrated in the field at small angles gradually attenuates

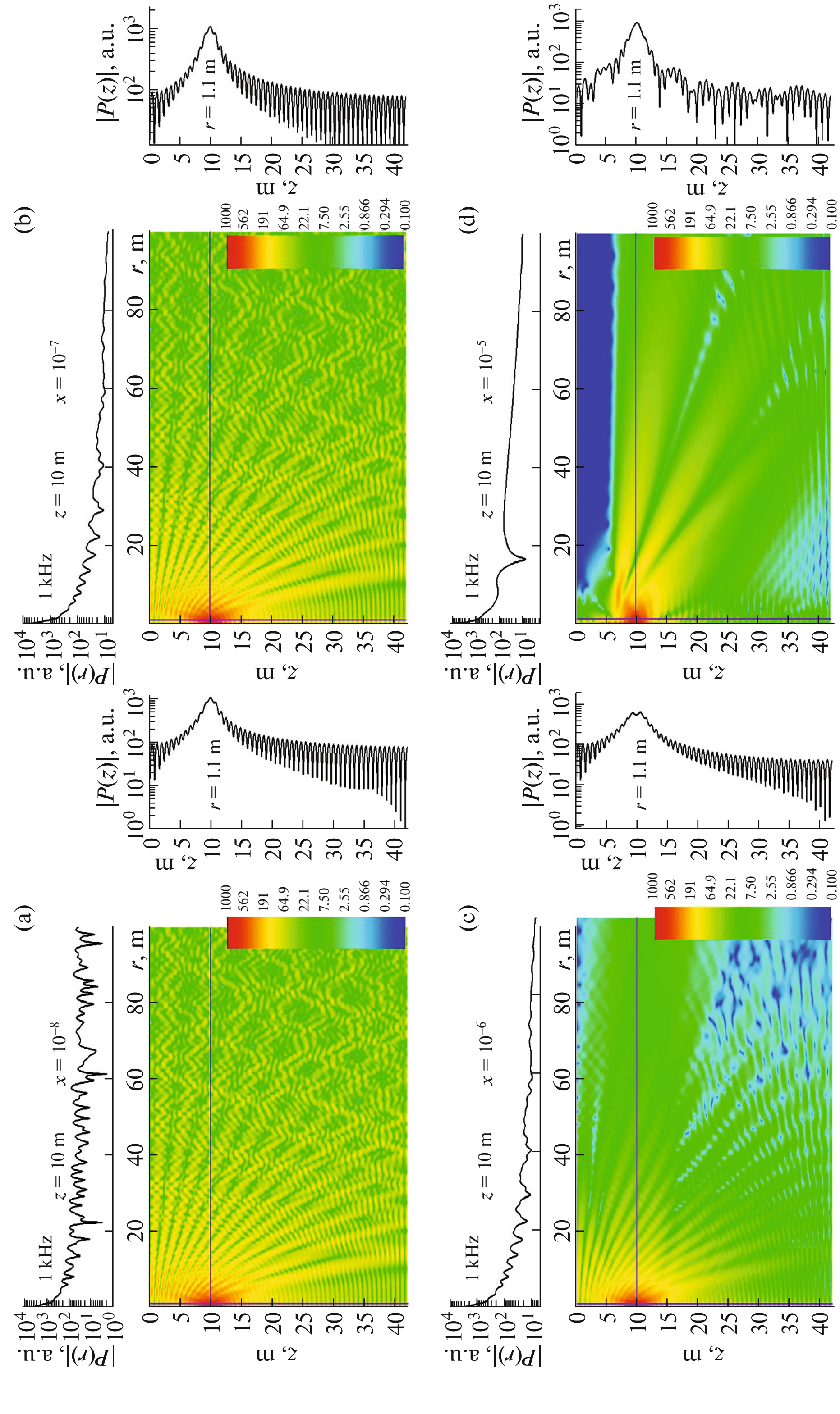

Fig. 3. Acoustic field with a frequency $f = 1$ kHz for radiation from a depth of 10 m in an isovelocity channel with a depth of 42 m in the presence of a near-surface bubble layer 7 m thick with a different concentration of bubbles: (a) $x = 10^{-8}$, (b) 10^{-7}, (c) 10^{-6}, and (d) 10^{-5}.

and does not contribute to the resultant field at large distances, which leads to the absence of a contribution from the bubble layer in the exponential law.

For more detailed study of the absorption effect in the presence of the near-surface layer of bubbles on the field structure along the sound propagation path, numerical modeling was performed using the normal mode approach. The model of the simplest horizontal homogeneous isovelocity underwater sound channel with absolutely reflecting boundaries (the upper boundary is soft; the lower boundary is hard) was selected. The sound pressure is represented as the sum of normal modes. Additional attenuation caused by the occurrence of the bubble layer is described by the imaginary part of the eigenvalues of the modes. The calculations of the sound field were performed using the KRAKENC program [12] for interacting modes. The thickness of the bubble layers was taken as 7 m. The source of the tone signal with the frequency f = 1 kHz was located at a depth of 10 m.

Figure 3 presents a 2D image of the acoustic field for different concentrations of bubbles in the near-surface layer. The calculations show a strong change in the structure of the acoustic field when the bubble concentration equal to 10^{-6} is exceeded. Especially impressive is the result for the concentration of 10^{-5}. Here, the field decays already in the vicinity of the emitter, and the general structure of the acoustic field in the waveguide changes sharply.

The expression for the resultant field $P(r) = \int_0^h p(r, z)dz$, where h is the channel depth, can be written as $P(r) = A\exp(-\alpha r)/\sqrt{r}$, according to which we can calculate the coefficient of sound attenuation α during propagation along the path in the presence of the near-surface layer with a different concentration of bubbles. The results of calculating the coefficients of sound attenuation α along the path with a distance of 100 m show the following values of α: $\alpha = 1.5 \times 10^{-6}$ 1/m at $x = 0$; $\alpha = 9.5 \times 10^{-4}$ 1/m at $x = 10^{-8}$; $\alpha = 7.4 \times 10^{-3}$ 1/m at $x = 10^{-6}$; $\alpha = 2.3 \times 10^{-3}$ 1/m at $x = 10^{-5}$. For comparison, for the case of a homogenous film of bubbles in seawater, the coefficient of absorption of the plane sound wave α_b at the frequency of 1 kHz has the following values: $\alpha_b = 1.5 \times 10^{-6}$ 1/m at $x = 0$; $\alpha_b = 3.5 \times 10^{-3}$ 1/m at $x = 10^{-8}$; α_b = 0.32 1/m at $x = 10^{-6}$; and α_b = 2.0 1/m at $x = 10^{-5}$. As a result, it turns out that, in the sea due to the small thickness of the bubble layer, the sound absorption is significantly less than in the case of absorption in a homogenous film of bubbles. Nevertheless, the value of the total coefficient of absorption at small distances is rather large compared to absorption in pure seawater. However, at an increase in the concentration $x > 10^{-6}$, the coefficient α starts to decrease sharply even at small distances.

Thus, it is shown that the effect of the near-surface layer of bubbles consists in the additional decay of the field at moderate distances, which is caused by attenuation of a part of the sound energy propagated through the bubble layer. Further, this energy is attenuated, which results in the absence of the contribution of the bubble layer in the exponential law. Note that the occurrence of dissipation in the near-surface layer of bubbles can lead to significant restructuring of the acoustic field, as is demonstrated in Fig. 3. The results obtained are new, predict rather unexpected behavior at a change in the properties of the bubble layer, and require urgent experimental verification due to the importance of the conclusions derived.

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