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Abstract

Full Text

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GEOPHYSICS

Yu. Yu. ZHITKOVSKII

PROPERTIES OF SOUND SIGNALS REFLECTED BY THE OCEAN SURFACE

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Recently published works devoted to the reflection of sound by a rough sea surface have dealt with the statistical characteristics of the reflected signals. In the present work, the angular and frequency dependences of the effective reflection coefficient were also investigated.

In the investigations a new method was used, making it possible to carry out measurements from a single vessel. An omnidirectional sound receiver was suspended from a float at a depth of 150 m and was paid out on a cable-rope over the side of a drifting vessel (see Fig. 1). The cable-rope was kept on the ocean surface with the aid of a large number of small floats. The transmitter, lowered from the side of the vessel likewise to a depth of 150 m, was oriented in such a way that the signal reflected by the surface reached the sound receiver. The azimuth of the sound receiver was determined from the direction to the terminal float with the aid of the standard shipboard visual direction finder.

Fig. 1. Experimental arrangement. 1 –sound receiver, 2 –terminal float, 3 –floats, 4 –transmitter, 5 –vessel

The work was carried out in May 1967 with a sea state of about 3 points and a wind speed of 4 ± 0.5 m/sec, in individual cases up to 5.5–7.5 m/sec. The wave height was ~1.5 m. The vertical profile of the sound speed made it possible to assume that, in the range of angles of incidence (23° – 80°) at which the measurements were made, the medium was isovelocity. At some distances, in order to measure the pressure level in the direct signal, the transmitter was oriented with the maximum of its directivity pattern toward the sound receiver. The angle of incidence was determined by the distance between the transmitter and the receiver.

Fig. 2

Figure 2: Fig. 2

For each angle of incidence (distance), at each of the four frequencies 1, 2, 4, and 8 kHz at which measurements were made, more than 200 reflected tone-pulse signals were recorded. The duration of the video pulse was 10 msec, and the repetition period was 1 sec. The width of the transmitter directivity pattern at the 0.7 level was 60°, 30°, 15°, and 8° at frequencies of 1, 2, 4, and 8 kHz, respectively.

Calculations of the effective reflection coefficient were carried out according to the formula:

$$V = \frac{R}{R} \sqrt{\frac{p^2}{p^2}}, \quad (1)$$

where V is the effective pressure reflection coefficient, p is the pressure in the reflected signal at the receiving point, p is the pressure in the direct signal at the receiving point, R is the length of the path traversed by the reflected signal from the source to the receiver, and R is the length of the path traversed by the direct signal from the source to the receiver.

Fig. 2. Dependences of the coefficient of variation on the angle of incidence at frequencies of 1 kHz (a), 2 (b), 4 (v), and 8 kHz (g)

Absorption of sound during its propagation in water could be neglected, since even at the highest frequency (8 kHz) the error due to neglecting absorption, in the worst case (at an incidence angle $\theta = 80^\circ$), did not exceed 0.7 dB.

In order for an uneven surface to be characterized by an effective reflection coefficient, the width of the directional pattern of the source (with a nondirectional receiver) must be no narrower than half the width of the scattering indicatrix of the surface. An estimate was made of the half-width of the surface-scattering indicatrix, based on the fact that the duration of the reflected pulse at all frequencies and at all incidence angles was equal to the duration of the emitted pulse. The calculations showed that the half-width of the indicatrix was no more than 2° at $\theta = 80^\circ$, 7° at $\theta = 45^\circ$, and 12° at $\theta = 30^\circ$. Thus, practically at all incidence angles and at all frequencies the width of the source directional pattern was greater than the half-width of the scattering indicatrix.

In addition to the values of the effective scattering coefficient, the coefficients of variation of the amplitudes of signals reflected by the ocean surface were calculated according to the formula

$$\eta = \sqrt{\left(\overline{A^2} - \overline{A}^2\right) / \overline{A}^2}, \quad (2)$$

Fig. 3

Figure 3: Fig. 3

where A is the amplitude of the envelope of the reflected signal. As can be seen from Fig. 2, under the hydrometeorological conditions that occurred, at all incidence angles from 23° to 80° and at all frequencies from 1 to 8 kHz, the coherent component in the reflected signal was practically absent. The exception was the frequency of 1 kHz at the angle $\theta = 80^\circ$, at which $\eta = 20\%$, which may be explained by the small value of the Rayleigh parameter* under these conditions.

Let us turn to an analysis of the angular dependences of the effective reflection coefficient presented in Fig. 3. As is evident from the graphs, even a slight increase in wind reduces the value of the reflection coefficient.

Despite the nonuniformity of the meteorological conditions, a clear tendency is observed for the reflection coefficient to increase with increasing angle of incidence. This tendency is disrupted only at incidence angles of 75° and 80° , which can be explained by a sharp increase in wind speed—from 4 to 7.5 m/s.

* To determine the degree of smoothness of the reflecting surface, Rayleigh introduced the parameter $\Phi = kH \cos \theta$, where k is the wave number, H is the mean value of the height of the irregularities (from maximum to minimum), and θ is the angle of incidence. Values of the Rayleigh parameter $\Phi \ll 1$ correspond to reflection from a practically smooth boundary.

At small angles of incidence the reflection coefficient is approximately equal to 0.7, increasing to 0.95 at large angles of incidence. The result obtained requires additional analysis. If the coefficient of sound reflection from a plane boundary between two media does not depend on the angle of incidence and is equal in modulus to unity, then in the case of reflection from a rough boundary between the same media the effective reflection coefficient for $\Phi \gg 1$ (i.e., if the coherent component is absent) must also be equal to unity, provided that the half-width of the indicatrix is less than the width of the transmitter directivity pattern for a nondirectional receiver and the maximum of the indicatrix is close to the direction of specular reflection from the mean plane.

Fig. 3. Angular characteristics of the effective reflection coefficient. The numbers correspond to the wind speed that occurred during measurement of the reflection coefficient; the dashed line shows the curve constructed according to (4). The notation is the same as in Fig. 2.

The fulfillment of the latter condition was established experimentally. Consequently, the requirement on the width of the transmitter directivity pattern was not fully satisfied. A careful examination of the records of the reflected signals showed that sometimes there is a slowly decaying trailing edge of the signals, small in amplitude and apparently, as a rule, lying below the level of the ambi-

ent noise. This scattered energy was not taken into account in calculating the effective reflection coefficient. It is apparently caused by scattering of part of the incident energy over a wide range of angles. The cause of this scattering may be both steep surface irregularities and the layer of water adjacent to it, saturated with air bubbles. The existence of such scattering is confirmed by the angular characteristics of the coefficient of sound scattering in the backward direction, from which it is seen that even at the most grazing angles a scattered signal propagates in the backward direction (i.e., in a direction almost opposite to the specular one).

Thus, it may be assumed that the scattering indicatrix of the sea surface has a complex form: in directions close to the specular one there is a narrow part carrying the main fraction of the scattered signal, while in other directions the scattering coefficient is considerably smaller.

Let us estimate quantitatively how much the effective reflection coefficient should decrease due to scattering in different directions. For this purpose we shall use data obtained by other investigators in measuring the coefficient of sound scattering by the ocean surface in the backward direction [1]. For the angular dependence of the coefficient of scattering in the backward direction, obtained under hydrometeorological conditions corresponding to the conditions of our experiment, a functional dependence of the form was selected

$$M_B = 0.1e^{-0.1\theta}, \quad (3)$$

where M_B is the coefficient of scattering in the backward direction, and θ is expressed in degrees.

If it is assumed that, when the angle of incidence changes, the shape of the indicatrix does not change, then at an angle of incidence θ the indicatrix, without changing shape, will decrease by a factor of $\cos \theta$, because of the decrease in the fraction of energy falling on a unit area of the scattering surface.

The effective reflection coefficient V , due to the narrow part of the indicatrix, which carries along directions close to the specular one the principal fraction of the energy scattered by the surface, must be equal to

$$V = \sqrt{1 - V_{\text{scat}}^2}, \quad (4)$$

where V_{scat}^2 can be written as

$$V_{\text{scat}}^2 = 2\pi \int_0^{\pi/2} M \sin \psi \, d\psi = 0.2\lambda \cos \theta \int_0^{\pi/2} e^{-0.05\psi} \sin \psi \, d\psi = 0.2\pi \cos \theta. \quad (5)$$

Substituting in (4) the values of V_{scat}^2 from (5), we obtain the effective reflection coefficient that should result if the decrease of the effective reflection coefficient in the specular direction is due only to the scattering obtained by us from the backscattering characteristics.

The values of the coefficient V obtained from formula (4) are plotted in Fig. 3 by the dashed line. Comparison of the graphs obtained by direct measurements with those calculated from the backscattering data shows good agreement of the results. Attention should be drawn to the fact that the integrand in expression (5) has a maximum at $\psi = 87^\circ$. This result makes it possible to draw the following important conclusion: if the directional pattern of the transmitter (or receiver) is wider than half the width of the narrow part of the indicatrix, then the measured value of the sound-scattering coefficient may be regarded as equal to the effective coefficient, since it will practically not depend on the width of the directional patterns.

In the frequency range 1–4 kHz no appreciable frequency dependence of the effective reflection coefficient is observed, which also agrees with data on the scattering of sound by the ocean surface in the backward direction. The somewhat smaller value of the coefficient at a frequency of 8 kHz is due partly to the neglect of sound absorption in water, and partly to the increase of scattering in directions far from the specular one.

In the work, dependences of the variation coefficient on the Rayleigh parameter of the amplitude distribution of the reflected signals were also obtained, as well as autocorrelation characteristics of fluctuations of the amplitudes of the reflected signals. The data obtained coincide with the results of work (2).

Acoustics Institute
Moscow

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