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Vector-phase methods of bottom reflecting properties research in shallow shelf area

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It is known that parameters of bottom have essential influence on the signal propagation in the shallow water. Variation of the attenuation coefficient can amount to tens dB. Therefore, research of bottom properties ant its structure (first of all – thickness and acoustic parameters of alluvial soil) is an actual problem, especially at low frequencies. Using of receivers, which record both, sound pressure and pressure gradient makes this easier to solve this problem in a number of cases. This paper deals with methods, which were developed and experimentally verified for areas with bottom depth 8-50 *m.* The following methods are considered: firstly, impedance method, which is based on direct measurement of relation between pressure and vertical component of oscillatory velocity in one point on the water/ bottom boundary; secondary, method, which is based on measuring phase difference between pressure and horizontal or vertical component of particle velocity; thirdly, method in which additive combination of sound pressure and vertical component of oscillatory velocity is used.

1 Introduction

One of the major problems of modern hydroacoustics is detection and localization of signals of the remote determined sources against the background of ocean noises. As long ago as W.S. Burdick specified importance of this problem under modern conditions in his well-known monograph *Underwater Acoustic System Analysis*. The solution of this problem is closely connected with solutions of two others. The first one deals with the ability to solve the problem of distant sound propagation in the ocean at extended lines. However, it is possible to solve this problem completely (especially for coastal, shallow water areas) only if we have trustworthy information about acoustic parameters of bottom. It is known that variations of sound attenuation at change of bottom properties sometimes can reach tens dB. Therefore, research of bottom properties and its structure is the heart of the second actual problem of hydroacoustics.

As a rule, sea bottom is not homogeneous and in most cases it can be presented like layers set of various thicknesses with different both sound speed and density. Thus, these low frequency acoustic signals penetrate into bottom at various depths which depends on many factors, including frequency, angle of wave incidence, acoustic impedance of bottom layers, etc. Presence of losses in underwater bottom layers offers significant difficulty in construction of bottom acoustic model. Therefore, the bottom acoustic model, which adequately describes interaction of water and bottom modes under propagation, is seldom possible to construct based on geological profiles. But bottom characteristic determined by acoustic methods in one frequency range practically can't be transformed to other frequency ranges. It means that bottom acoustic parameters, as a rule, are required to be determined for each area in which propagation of acoustic signals is studied and exactly in the tested frequency range.

It is supposed, that in high frequency range the problem of bottom parameters determination is more or less solved. As far as low frequency range is concerned, there are still a large number of problems. We shell describe only some approaches to the solution of this problem, established in our laboratory during the period of thirty years of theoretical and experimental researches. Since the beginning of the sixties a new direction in acoustics, vector-phase methods, were developed at the acoustics department of Physics Faculty of M.V.Lomonosov Moscow State University. One of the applications of these methods is the research of acoustic characteristics of underwater bottom at low sound frequencies. Measurement of sound pressure and sound pressure gradient in a wave allowed to expand the capabilities of research methods of reflecting bottom properties at low sound frequencies owing to simultaneous registering both amplitude and difference - phase relations between sound pressure and oscillatory velocity. Some of the worked out and experimentally tested methods of approach to the solution of the problems of determination of acoustic characteristics of bottom are being discussed in this paper.

2 Vector-phase methods of bottom properties research

2.1 Impedance method

The input impedance of layered bottom is defined by known recurrent formula [1] in terms of sound speed c_n and density ρ_n of bottom layer with number n, thickness of this layer h_n, incidence angle of acoustic wave on the bottom ϑ, frequency f, water wave impedance $Z_0=\rho_0 c_0$. The impedance and reflection coefficient $\mathrm{V}(\vartheta,f)$ are connected by a relation:

$$\mathrm{V}(\vartheta,f)=\left[Z_{\mathrm{in}}(\vartheta,f)-{Z_0}/{\cos\vartheta}\right]\Big/\left[Z_{\mathrm{in}}(\vartheta,f)+{Z_0}/{\cos\vartheta}\right]. \quad (1)$$

Input impedance is determined by measurement of sound pressure P and vertical component of oscillatory velocity V_z in one point on the water/ bottom boundary H:

$$Z_{\mathrm{in}}=(P/V_Z)\big|_{z=H}.$$

Value of input impedance depends on the horizon of receiving system localization. If position of effective reflecting surface does not correspond with real bottom in examined frequency range, there are errors in the determination of reflection coefficient module. As a result, impedance method requires exact knowledge of experiment layout and can be effective only in high frequency range.

2.2 Use of amplitude relations between field components

The method consists of simultaneous registering of sound pressure and vertical component of oscillatory velocity. If ϑ is the incidence angle of sound wave to the bottom, the method allows to determine module of reflection coefficient by relation [2]:

$$|V(\vartheta)| = \frac{P\cos\vartheta - V_z}{P\cos\vartheta + V_z}. \quad (2)$$

The essence of this method is the formation of minima of receiving system directional characteristic in the direction to the signals propagating from surface to bottom (numerator) and, on the contrary, reflected from bottom (denominator). Unnecessary for receiving system to move along vertical line during measurements essentially reduces the time of measurements. This method allows to lower threshold frequency of working range, but needs careful adjustment of the amplitude and phase characteristics of receiving system including both receiver of pressure and receiver of pressure gradient.

In one of our experiments comparative definition of module of reflection coefficient $|V|$ by two ways has been checked: by the method described above and interference method. These measurements have been carried out in the Black Sea shelf area with 28 *m* depth and 0.5 *miles* distance from the shore. In the first case measurements have been carried out at frequency range 90… 600 Hz by two regimes: the receiving system was located at the bottom and at 2 *m* above it. In the second case, vertical profiles of pressure near the bottom were registered twice on each frequency: during lowering and lifting up the receiving system. Then the radiator was moved in other horizontal position and measurements were repeated. The module of reflection coefficient was defined by the Eq.(3), where $P_{\max}$ and $P_{\min}$ were the values of sound pressure in the maximum and the minimum of the interference pictures [3]:

$$|V| = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}}. \quad (3)$$

Values $|V|$ as function of frequency for incidence angles $\vartheta \sim 2^0$ (*a*) and $\vartheta \sim 18^0$ (*b*) are shown on the Fig.1. Points mark the data received by interference method, crosses – by Eq.(2), when the receiving system being at the bottom. Obvious minima at frequency dependence testify the layered structure of bottom. Good conformity of values $|V|$, defined by two methods, is observed. For interpretation of the experimental characteristics model of a two-layer bottom (continuous curve) was used.

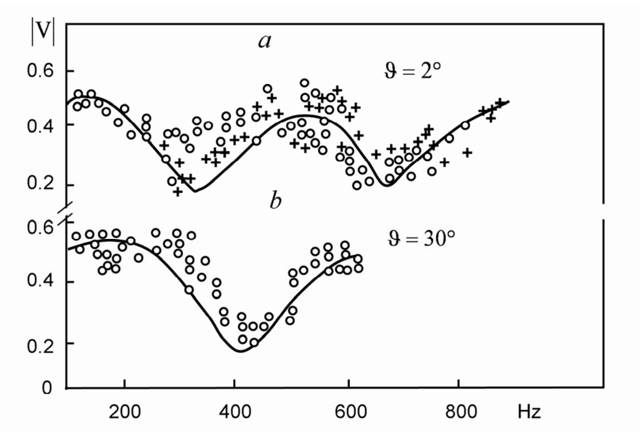

Fig.1 Module of reflection coefficient by Eq.(2) and (3).

In the case of low frequencies and shallow water area the distance between adjoining minima and maxima can be the same order as the depth of water; in order to decrease systematic error, it is proposed to use both profiles of pressure field *P* and field of the oscillatory velocity vertical component V_z. Reflection coefficient module $|V|$ is defined by Eq.(4), where all values of the maxima and minima of interference patterns were measured near the bottom.

$$|V| = \frac{P_{\max} - V_{z\min}}{P_{\max} + V_{z\min}} \quad |V| = \frac{V_{z\max} - P_{\min}}{V_{z\max} + P_{\min}}. \quad (4)$$

Values $|V|$ as function of frequency for incidence angle $\vartheta \sim 2^0$ are shown on the Fig.2. Points mark the data received by interference method and Eq.(4). These measurements have been carried out in the Baltic Sea shelf area with 15 *m* depth. For interpretation of the experimental data, models of a two- and three-layer bottom were used (continuous and dotted lines).

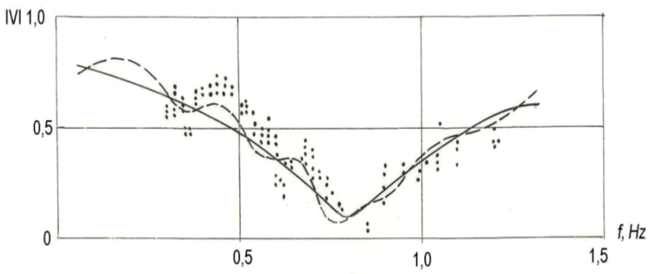

Fig.2 Module of reflection coefficient by Eq.(4).

2.3 Measurement of phase difference between pressure and component of oscillatory velocity

At low sound frequencies when length of wave and depth of a water layer are of the same order, research of the bottom acoustic properties can be carried out by measurement of phase difference between pressure and components of oscillatory velocity. This method can be used for determination of bottom parameters in any cases where relation between *P* and *V* is established. However such measurements are most practical to carry out at flat bottom where this relation is the most simple.

Horizontal component. For acoustically "soft" ground ($c_1 \leq (0{,}1 - 0{,}4)c_0$) and flat water layer, equation for phase difference between sound pressure and horizontal component of oscillatory velocity, for mode *n* and for distances $|m_n r| > 1$ is:

$$\Delta\varphi(P_n V_{xn}) = arctg(m_n'' / m_n') + (1 / r m_n' \sqrt{2}), \quad (5)$$

where m_n and l_n are horizontal and vertical components of a wave vector in water layer $k_0 = m_n^2 + l_n^2$, m'_n and m''_n are real and imaginary parts of horizontal component of wave vector, *r* is distance from source to receiver. By measuring phase's difference between P_n and V_{xn} at two horizontal distances r_1 and r_2 for frequencies, when one normal mode *n* propagates in water layer, it is possible to determine values m'_n and m''_n and, consequently m_n.

For model of bottom as homogeneous liquid semi space, the vertical component of a wave vector is:

$$l_n = n\pi / H(1 + i\rho_1 c_1 / \omega\rho_0 H),$$

where ρ_1 and c_1 are real parts of density and speed of a sound in a bottom, $\omega = 2\pi f$ - circular frequency of a signal, H - depth of water layer. For distances $r>10\lambda$ (λ is length of sound wave) Eq.(5) could be simplified and equation for calculation of acoustic impedance of bottom ($\rho_1 c_1$) for mode n depending on $\Delta\varphi(P_n V_{xn})$ is:

$$\Delta\varphi(P_n V_{xn}) \approx \frac{1}{2} arctg \frac{\pi\rho_1 c_1 n^2}{\rho_0 f H^3 + [k_0^2 - \left(\frac{\pi n}{H}\right)^2 + \left(\frac{\rho_1 c_1 n}{2\rho_0 f H^2}\right)^2]}$$

Experimental data of phase difference $\Delta\varphi(P_n V_{xn})$ as the function of frequency are presented on Fig.3, where triangles, crosses and squares correspond to distances between source and receiving system r = 4 *m,* 14 *m* and 100 *m*. Continuous curves 1 and 2 correspond to calculated data of phase difference for r = 4 *m,* 14 *m* and two-layer bottom model. Character of both experimental and calculated data is similar in the frequency range 100-190 Hz. The deviation in the frequency range 200-230 Hz is caused by appearance of the second normal wave in water layer.

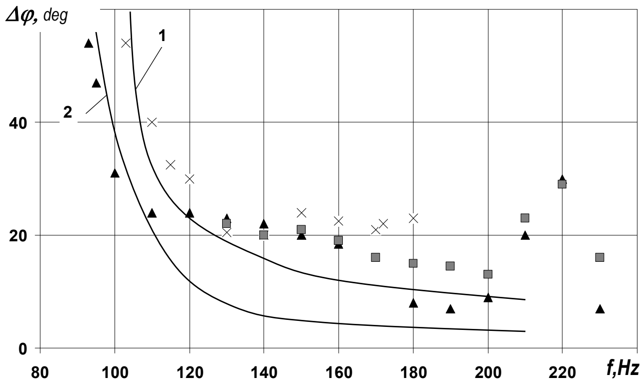

Fig.3 Phases difference between P_n and V_{xn}

The suggested method of definition of the bottom acoustic characteristics has been checked in shallow water area with H=7.5 *m*. Bottom acoustic characteristics were defined also by measurement of sound pressure decrease in function of horizontal distance. Average values of acoustic impedance of the bottom, which were defined by these two methods, differ no more than by 15 % in frequency range 100-180 Hz. Obviously, that for realization of this method it is necessary to select separate normal mode, easiest by using the frequencies close to critical. Dependence of experiment results on horizontal distance from source is shortage of this method.

Vertical component. Phase difference between sound pressure and vertical component of oscillatory velocity V_{nz} is determined as follows [4]:

$$\tan\Delta\varphi(P_n V_{zn}) = \frac{l_n' \sin(2 l_n' z) + l_n'' sh(2 l_n'' z)}{l_n'' \sin(2 l_n' z) - l_n' sh(2 l_n'' z)}, \quad (6)$$

where z is vertical coordinate, l'_n and l''_n are real and imaginary parts of vertical component of wave vector. Eq.(6) is invariant to the model of bottom and is independent from horizontal distance between source and receiving system. The reflection coefficient of plane sound wave from water/ bottom boundary is connected with vertical component of wave vector by dispersive equation $V_1 V e^{-2ilH}=1$, where V_1 and V are reflection coefficients from water/ air and water/ bottom boundary. In case $V_1=1$ and $l = l_n^{/} + i l_n^{//}$ dispersive equation is $V = |V|\, e^{2ilH}$, where $|V| = e^{-2i\, l''H}$. Accordingly l'_n determines the module of reflection coefficient $|V|$ and l''_n – its phase.

Theoretically calculated values of phase difference $\Delta\varphi(P_n V_{zn})$ between sound pressure and vertical component of oscillatory velocity for mode n and for model of two-layer bottom are shown on the Fig.3, where H = 8 *m* and z = 0,7 *H*. Characteristics of lower half space are: sound velocity c_2 =1800 *м/sec* and ground density ρ_2 = 1,8g/*cm*^{3}. Frequency dependences 1, 2 and 3 correspond to sound velocities c_1 =100 *m/sec, 150 m/sec и 200 m/sec* in the intermediate layer of thickness h = 0,7 *m* and ρ_1 =1,6 *g/cm*^{3}

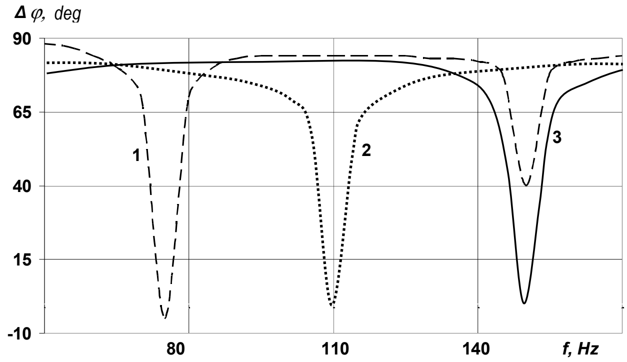

Fig.4 Phases difference between P_n and V_{zn}

Frequency dependences of phase difference have oscillatory character: positions of minima significantly depend on sound speed in an intermediate layer of bottom. Positions of minima coincide with frequency dependence maxima of imaginary parts of vertical component of wave vector for identical parameters of bottom model. Frequency dependence $\Delta\varphi(P_n V_{zn})$ for the bottom model which can be considered as watery half space has monotonous character and increases, coming to 90^0. As a result, it is possible to classify acoustic model of a ground, homogeneous or layered ground model, by experimental frequency dependence between sound pressure P_n and vertical component of oscillatory velocity V_{zn}. By measuring phase differences of $\Delta\varphi(P_n V_{zn})$ on two vertical distances for depth of a water layer and the fixed frequency it is possible to calculate values $l_n^{'}$ and $l_n^{''}$.

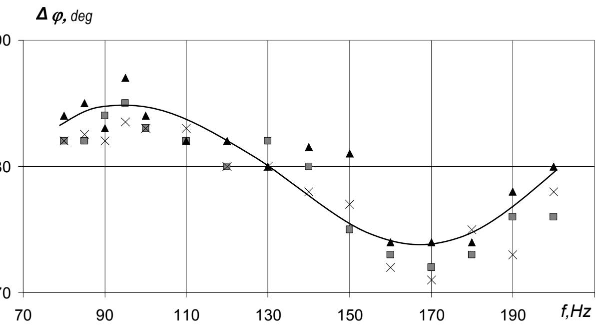

Fig.5 Phases difference between P_n and V_{zn}

Experimental data of phase difference $\Delta\varphi(P_n V_{zn})$ as the function of frequency for shallow inland water area are presented at Fig.5, where squares, triangles and crosses correspond to data at distances between source and receiving system r = 10 *m,* 20 *m* and 50 *m*. Measurements were made on depth Z = (0,7 – 0,8) H, because change of phases difference in function of vertical coordinate z for this range is minimal, according to our estimations. And inaccuracy of receiving system set up will not result in essential errors of definition of bottom parameters.

Phase difference $\Delta\varphi(P_n V_{zn})$ is independent from horizontal distance between source and receiving system in the explored frequency range. This frequency dependence of phase difference can't be accounted for by homogeneous water semi space bottom model. Calculated values of phase difference $\Delta\varphi(P_n V_{zn})$ between sound pressure and vertical component of oscillatory velocity for the first mode and model of two-layer bottom are shown by continuous curve, where sound velocity c_1 =340 *m/sec* and thickness of intermediate layer h = 0,7 *m* were used. In tested range of frequencies theoretically calculated frequency dependence of phase difference for two-layer model of bottom match well with experimental data.

3 Conclusion

Vector-phase methods at present contribute significantly to the improvement of hydroacoustic methods for solving acoustics applied tasks. Use of these methods allows working in lower frequency range. The suggested methods to study the acoustic bottom characteristics repeatedly have been checked in shallow shelf area of the Baltic and the Black Seas, and also at shallow inland water areas. The obtained results were used for calibration of vector receivers and definition of acoustic productivity of the directed sound sources at low sound frequencies.

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