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Estimation of Hydroacoustic Parameters of Bottom in Shallow Water Using Low-Frequency FM Signals[1]

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Method of data inversion for geoacoustic parameters of bottom using FM acoustic signals is presented. Frequency spectra of received signals are taken as input data for application of Matched Field Processing (MFP) method. For estimation of bottom parameters we use the two-components model of sediment. As a result of matching we obtain relationship between two mechanisms of loss: energy absorption and volume scattering within bottom sediment.

1. Introduction

It is known that we can find hydroacoustic parameters of oceanic waveguide using acoustic data. In shallow water bottom parameters play the main role in the forming of sound field structure, it means that data of acoustical probing can be used as input data for the finding of bottom parameters.

Presently, as the most usable method for this aim, the so called MFP (Matched Field Processing) method is used. Within the framework of this method we find set of bottom parameters giving minimal value of mismatch between theoretically calculated and experimentally measured data.

This method was actualized on the basis of different sets of input data. For example in [1] we used range dependence of sound intensity (horizontal interference structure), vertical interference structure was used in [2], in [3] we have taken frequency dependence of bright – band signal intensity. In the last reference we have considered frequency dependence of coefficient of losses in bottom. This coefficient was considered empirically, without specification of "microscopic" mechanisms responsible for energy loss. In presented work we try to reconstruct bottom parameters using more detail description of sediment.

2. Theoretical Background

Let's consider the following model of shallow water channel. Water layer with sound speed profile and density $c(z)$, ρ is placed over sediment half-space. These sediments are two-components media: water plus mineral particles. The main parameter, characterizing sediment is porosity κ , which is equal to volume filled by water in the unit volume of sediment. Within the framework of a little simplified theory of sea sediment, sound speed and density of bottom c_1, ρ_1 can be expressed through porosity [4]:

$$c_1 = c_H\left(1.631 - 1.78\kappa + 1.2\kappa^2\right), \quad (1)$$

$$\rho_1 = \rho_H\left(2.604 - 1.606\kappa\right), \quad (2)$$

where c_H , ρ_H are sound speed and density in water near the bottom. We will consider two mechanisms of bottom losses: literally absorption – transformation of sound energy into heart, and volume scattering. For the first from listed items we have (with great degree of accuracy) linear

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character of frequency dependence for absorption coefficient:

$$\beta_n = \beta_{nf} f \qquad (3)$$

where

$$\beta_{nf}\left[\frac{\text{dB}}{\text{km}\cdot\text{Hz}}\right] = \begin{cases} 0.2747 + 0.527\kappa, \kappa \in [0,0.472] \\ 4.903\kappa - 1.7688, \kappa \in [0.472,0.52] \\ 3.3232 - 4.89\kappa, \kappa \in [0.52,0.65] \\ 0.7602 - 1.5\kappa + 0.78\kappa^2 \ \ \kappa \in [0.65,0.9] \end{cases}$$

However, for β_{nf} there is rather great dispersion for different regions of Ocean.

The second mechanism responsible for the loss is volume scattering within bottom. This phenomenon is described by volume scattering coefficient β_p which is ratio of sound power W scattered in all directions to intensity I_0 of incident wave:

$$\beta_p = \frac{W}{I_0} \qquad (4)$$

It is known, that for different types of scatterers frequency dependence of β_p can be described by formula

$$\beta_p = \beta_{pf} f^b \qquad (5)$$

where β_{pf} specific coefficient of volume scattering, parameter $b = 2.5 \div 4$, this parameter is determined by dominating types of scatterers in bottom.

Finally for bottom coefficient of loss we have:

$$\beta = \beta_{nf} f + 0.5\beta_{pf} f^b \qquad (6)$$

So within the framework of presented waveguide model sound field from point source is sum of modes:

$$u(\mathbf{R}, f) \approx -A(f)\sqrt{\frac{i}{8\pi}} \sum_n \psi_n(z_0)\psi_n(z)\frac{\exp(i\xi_n r)}{\sqrt{\xi_n r}} \qquad (7)$$

where complex coefficient $A(f)$ determines power $W(f)$ and initial phase of the source: $|A(f)| = \sqrt{8\pi\rho_H c_0(z_0)W(f)}$,

$\psi_n(z)$ and ξ_n are eigen function and complex eigen values of the Sturm problem:

$$\begin{cases} \left[\frac{d^2}{dz^2} + k_0^2 - \xi_n^2\right]\psi_n(z) = 0; \\ \psi_n(0) = 0;\ \psi_n(H) + \frac{m}{\sqrt{\xi_n^2 - k_1^2}}\left.\frac{d\psi_n(z)}{dz}\right|_{z=H} = 0. \end{cases} \qquad (8)$$

where $0 \le z \le H$, If $z \ge H$ then

$$\psi_n(z) = \psi_n(H)\exp\left[-\sqrt{\xi_n^2 - k_1^2}(z-H)\right], \qquad (9)$$

$$k_1 = \frac{2\pi f}{c_1} + i\beta \text{, or } k_1 = \frac{2\pi f}{c_1}\left(1 + i\frac{\alpha}{2}\right) \qquad (10)$$

In our model coefficient $\alpha = \frac{\beta c_1}{\pi f}$ is used for description of bottom loss. According to formula (6) it can be presented as sum of two terms each of which is responsible for its own mechanism of loss:

$$\alpha = \alpha_n + \alpha_p \quad (11)$$

where α_n and α_p correspond to absorption of energy and volume scattering respectively.

For the matching theoretical and experimental data we can use different criteria. For example, let we have experimental $|u|_i^{\exp}$ and theoretical $|u|_i^{theor}$ spectra which are a set of M frequency values of sound amplitude at the point of observation:

$$|u|_i = |u(\mathbf{R}, f_i)|,\ i = 1,\ldots,M .$$

We can consider these sets as two M-dimensional vectors

$$\mathbf{E} = \left\{|u|_i^{\exp}\right\} \text{ and } \mathbf{T} = \left\{|u|_i^{theor}\right\}.$$

Theoretical vector is determined by set of parameters of our waveguide model. Choosing these parameters we should minimize mismatch between mentioned two vectors Mathematically it corresponds minimization of value (for example):

$$\sigma = \frac{|\mathbf{E}-\mathbf{T}|}{|\mathbf{E}|+|\mathbf{T}|}100\% = \sqrt{\frac{\sum_{i=1}^{M}\left(|u|_i^{\exp} - |u|_i^{theor}\right)^2}{\sum_{i=1}^{M}\left(|u|_i^{\exp}\right)^2 + \sum_{i=1}^{M}\left(|u|_i^{theor}\right)^2}}100\%$$

3. Experiment and Matching Processing

Let's consider application of presented theory on the example of experiment with FM-modulated signals in Barents Sea.

Experiment was conducted at the stationary track between two ships. The source radiated linearly modulated low-frequency signals during about 2 hours within the band 25-95 Hz.

There was 100 pulses with duration of each about 40 sec with period 60 sec. Source depth was about 70 m? distance between source and receiver was fixed (about 13.82 km). Depth of channel was approximately constant $H \approx 170$ m, sound speed profile had a little negative gradient in direction to bottom. One example of received spectrum is shown on the fig.1. On the fig 1a real spectrum is presented, we can sea oscillating interference structure.

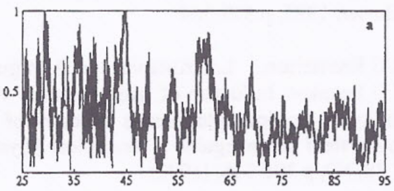

Fig. 1a. Experimental spectrum of received signal (frequency in Hz)

After averaging with sliding window we can obtain more regular picture. Fig 1b corresponds scale of averaging 1Hz and fig 1c corresponds to sliding window 5 Hz.

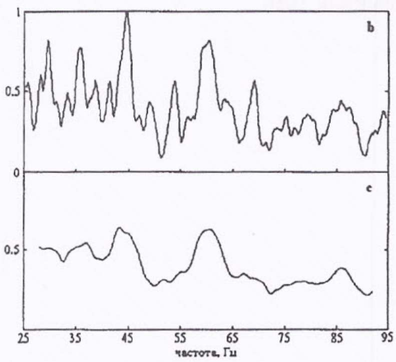

Fig 1b and 1c. Averaged spectra of received signal (frequency in Hz)

Calculations of spectra of received sound signals are made within the framework of the model of shallow water channel based on measured characteristics (sound speed profile, water depth etc). The new element in our approach (for MFP-method) is modeling of bottom using parameters of sediment given by two-component model of Biot-Hamilton: porosity and coefficients of sound absorption and volume scattering in bottom layer. These parameters (having distinct frequency dependencies) are used as parameters of matching in MFP-method. More precisely we find optimal value of parameters κ, giving sound speed and density of bottom (formulae (1,2)), and $b, \beta_{nf}, \beta_{pf}$ which describe energy loss in sediment (formulae (6,11)).

This approach gives a good agreement between experimental and theoretical spectra for reasonable geoacoustic parameters (correspondingly parameters of two-component model). These parameters are presented in Table 1

Table 1. Optimal values of bottom parameters

κ	c_1 m/s	ρ_1 g/cm^3	β_{nf} m^{-1}Hz^{-1}	β_{pf} m^{-1}Hz^{-4}
0.3	1765	2.1	9.5 10^{-6}	3.3 10^{-10}

On the fig 2 and fig 3 we show experimental spectrum and theoretical one, corresponding to mentioned bottom parameters. We can see rather good agreement between both averaged over 1 Hz window and 5 Hz window frequency dependencies.

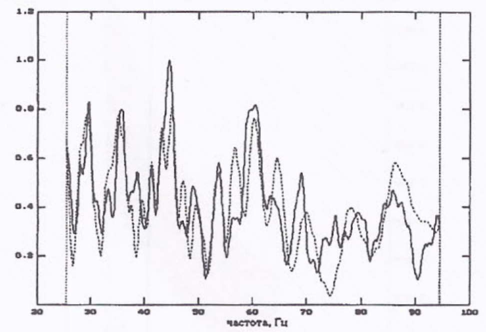

Fig.2 Experimental (solid line) and calculated (dotted line) spectra of received signal averaged by the 1 Hz-window.

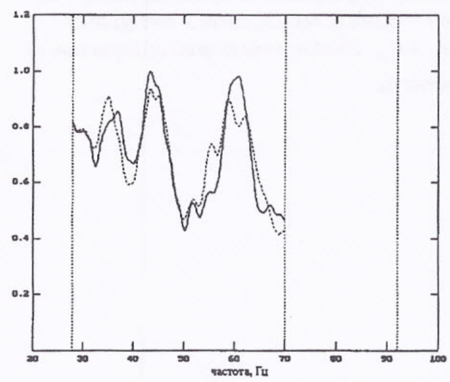

Fig3. Experimental (solid line) and calculated (dotted line) spectra of received signal averaged by the 5 Hz-window.

For usually used coefficient α we obtain

$$\alpha = 0.05 + 9.3 \cdot 10^{-8} (f[\text{Hz}])^3$$

These dependencies are shown on the fig.4 together with possible dispersion of values (shadow area)

4. Conclusion

Presented technique allow us to distinct mechanisms responsible for losses of the sound energy in bottom sediment. Namely coefficient α contains two terms - α_n - energy absorption and α_p - volume scattering. These two components are shown on the fig.4 separately. We can see that these terms have distinct frequency dependencies, on low frequency (less then 40 Hz) bottom absorption dominates and energy loss is conditioned by absorption in the great degree, on the other side, for more high frequency loss in sediment is conditioned by volume scattering

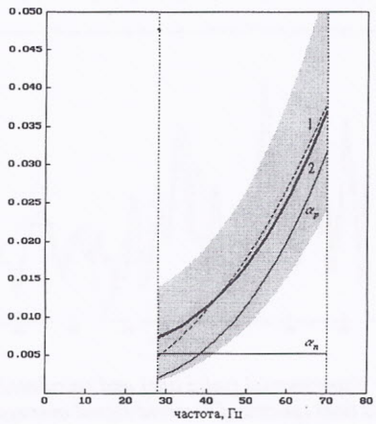

Fig.4 Frequency dependence of coefficients of loss. Curve 1 – result of ref. [3],curve 2 corresponds $\alpha = \alpha_n + \alpha_p$. *Shadow zone is area of dispersion of parameter* α

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