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RECONSTRUCTION OF THE WAVEGUIDE PARAMETERS BY RESULTS OF MODE SELECTION WITH USING THE PEKERIS MODEL

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In the present paper the results of testing of the medium matched method for mode selection are given. The method uses replicas built on the basis of the Pekeris model of a shallow sea [Zverev V.A., et al. Determination of the mode composition… // Acoustical Physics, V. 51, N2, 2005, P. 175-181]. By means of numerical modeling the applicability of the method for various hydrologies is illustrated. The testing has shown not only applicability of the method, but also possibility of estimation of the water layer parameters and the waveguide bottom characteristics practically for all typical hydrologies of the considered basin. The comparison of the bottom characteristics of the considered models with the experimental data has confirmed the possibility of reconstruction of the average waveguide characteristics. *This work was supported by the RFBR (projects № 04-02-17193, № 05-05-64432) and grant of the president of Russian Federation «Leading scientific schools» № НШ-10261.2006.2.*

The sound signal propagating in the shallow sea can be presented as a sum of separate modes (normal waves) being eigenfunctions of a waveguide, distinguishing by a propagation speed, a shape of a vertical profile and having a dispersion. Other presentations (for example, the ray presentation) with reference to the given waveguide require considerably greater analytical (and numerical) expenses, therefore they used seldom enough, especially at low frequencies. At the same time, practical usage of the mode presentation encounters some difficulties due to incompleteness of information about the waveguide parameters. This caused by impossibility of the recording of bottom characteristics essentially influencing on a dispersive propagation.

From the point of view of the mode selection (and determination of their characteristics), the best approach is the matched filtering coordinated with a signal and a medium. There are well-known methods for mode selection with certain accuracy using the spatial and temporal matched filtering of signals.

The spatial (vertical) selection of modes requires application of developed vertical receiving systems and knowledge of a shape of modes. The modes are described by the system of orthogonal functions that should guarantee high selection properties of the method. However, it is usually impossible to receive data from a whole depth of a waveguide and, furthermore from a sediment layer and a bottom. That results in infringement of the orthogonal properties. As the corollary, it does not allow to receive weakening of the nearest modes at the output of filter more than 10 -15 dB. Therefore, the selection based on a vertical Fourier transform got enough wide distribution. The transform has various modifications including a little bit raising selection possibilities [1]. The time selection requires usage of wide-band signals of the known shape, and up to recently it seldom used in a view of restricted technical capability of radiation of such signals. The appearance of modern broadband sources has forced to pay more attention to the temporal matched selection of modes. In the scientific publications, such method of a matched filtering has the settled definition as Match Field Processing (MFP). However, a substantially dispersive propagation of sound signals in a shallow sea requires a prior estimate of dispersion properties of shallow-water waveguides that is not always possible in practice.

In the present paper, the dispersion properties of so-called "three-layer" hydroacoustic waveguides are investigated by means of numerical modeling. Such waveguide consists of a water layer, a sediment layer and a stratum of basement rocks. Since such waveguide has the characteristics, close to actual ones, the comparison with it should give even qualitative estimates of opportunities of the proposed approach.

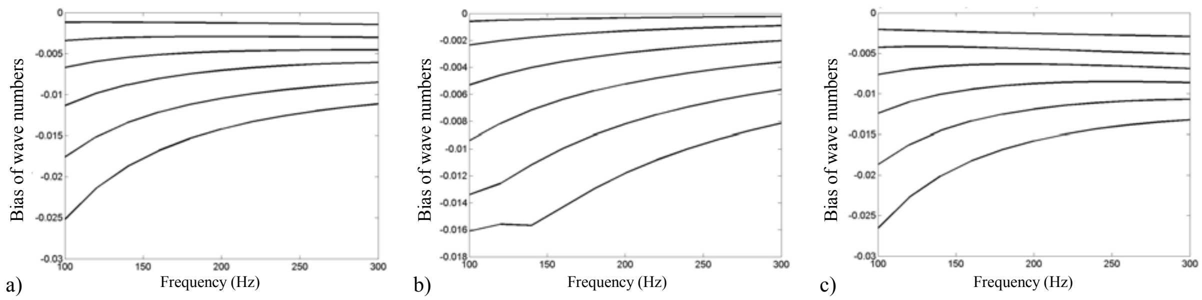

Рис. 1. Bias of wave numbers of the first six modes from a wave number of a homogeneous medium with sound speed equal minimum of a waveguide speed for miscellaneous hydrologies and sediment layers types. Experimental waveguide, sediment – sand (a), isovelocity waveguide, sediment – mud (b), linear waveguide, close to bottom, sediment – basalt (c).

The analysis shows that at a first approximation, the dispersion dependences of modes of such waveguides at high frequencies are similar to dispersion dependences of an isovelocity waveguide with absolutely reflecting boundaries, excepting the deflections from the monotonic frequency dependences of wave numbers at low frequencies [2] (Fig. 1b).

Actually the average value of a wavenumber and its frequency derivative can be approximated by simple analytical dependence (for example, polynomial), at least in finite frequency intervals.

The dispersion curve for the isovelocity waveguide with absolutely reflecting boundaries (soft and rigid) can be taken as such dependence [3]. The group velocity v_{gr} of sound in such waveguide takes the following form:

$$v_{gr} = c_0\sqrt{1-\frac{\pi^2 c_0\left(m-0.5\right)^2}{\left(\omega H\right)^2}} \approx c_0 - \frac{\pi^2 c_0\left(m-0.5\right)^2}{2\omega^2 H^2} \tag{1}$$

where m - the mode number, c_0 - the sound velocity in water, ω - the circular frequency of the signal, H - the thickness of the waveguide.

For the analysis of experimental data obtained from acoustic paths of definite length at frequencies above critical ones, the approximate relation for the mode delay with respect to the non-dispersed propagation time can be used:

$$\tau(\omega) = \frac{\pi^2 R c_0 (m-0.5)^2}{2\omega^2 H^2}, \tag{2}$$

where R - the distance between the source and the receiver.

In this expression the integer values of m correspond to a soft surface and a stiff bottom. If the values of m are non-integer, the sesquialteral values will correspond to a soft bottom, and remaining non-integer values – to intermediate impedances between a stiff and soft bottom [2]. It is obvious, that practically any monotonic dispersion dependence in a finite frequency interval can be approximated by the dependence (1) with varying values of the mode number, the waveguide thickness (the distance) and the frequency. It is necessary to note that the present dependence (in contrast to a polynomial function) does not allow describing deflections on the dispersion curves, however it gives information that is more physical.

For testing of the considered approach the numerical experiment was carried out. The frequency band 100 - 300 Hz was taken according to the experiment described in [4]. The typical parameters of the sediment layer were chosen according to [5, 6] as silt, sand, limestone and basalt. The characteristics of the basement corresponded to basalt. As vertical dependences of sound velocity in water the four profiles close to average ones for the Barents Sea were used:

1. Isovelocity, $c_0 =$ 1450 m/s;
2. Linear, close to surface (winter);
3. Linear, close to bottom (summer);
4. Experiment sound velocity profile.

For calculation of dispersion dependences of the actual waveguide the algorithm KRAKEN was used. The wave numbers were calculated for 11 frequencies of the operating band. For the same frequencies the dispersion dependences were calculated using (2). Then the minimum of the mean-square deviation (MSD) between these dependences was determined as the function from the mode number *m* in the considered frequency band.

The adjustment of the dispersion dependences (2) to the real waveguide can carry out by smooth variation of the mode number near the true value or, for example, variation of the waveguide thickness. The example of comparison of dispersion dependences in a frequency band 200-300 Hz at the adjustment by only numbers *m* is given in Fig. 2. In the figure the deflection of the curve corresponding to the three-layer waveguide (KRAKEN) is clearly displayed at low frequencies.

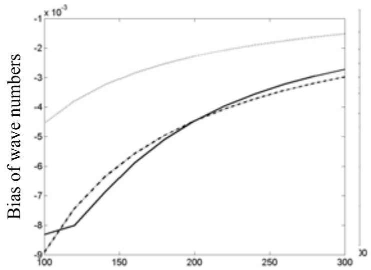

Fig.2. Dispersion dependences (deviation of group velocity from minimum sound speed in water) calculated by KRAKEN (solid line) The best fit with equation (2) (dash-dot line) and bias of m estimation from the best one (dotted). Mode #5, experimental waveguide, sediment – mud.

It is necessary to note that the matched filtering of complex signals causes narrowing of the time response of such filter in absence of dispersion. In dispersive media the limit of shortening of the pulse response equals the difference between signal delays caused by frequency variations of the propagation velocity. Therefore, the amplitude of wave number straggling in the operation frequency band is the measure of efficiency of the matched filtering without matching with medium. The relation of this straggling to the difference between the real dependence and the dependence forming the replica characterizes the efficiency of the applied MFP estimate of dispersion. As it follows from Fig. 2, even such approximate estimate of dispersion (2) allows contracting the time response of the signal with frequency band 100-300 Hz on the MFP filter output fivefold at the minimum.

Sometimes in real experiments, it is difficult to determine the absolute time delay. Therefore, there can be a necessity to execute searching not only by *m*, but also by the delay time, that considerably complicates a numerical analysis. Despite this fact, it is necessary to recognize usage of analytical dispersion dependences as more effective than precise numerical models (KRAKEN), particularly for solving of inverse problems, especially since the delay time in both cases is unknown even in required approach.

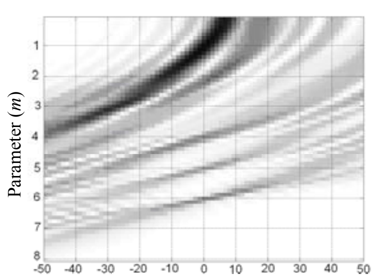

Fig.3. The output of matched filter at the adjustment of mode number *m* in equation (2).

Fig. 3 shows the result of the modeled matched filter with adjustment of *m* and the time delay. As it is well seen from the figure, the maximal response for each mode is observed approximately at the same delay, in this case – at zero-delay. However, it can fail for complex hydrologies. The figure also shows that as long as the delay estimation is exact, the mode selection is good enough (excluding, maybe, the first mode).

For the sound speed, profiles and the bottom characteristics given above the values of *m* corresponding to minimum of MSD were obtained for the first 10 modes. Fig. 4 presents some examples of the estimate of *m* for various hydrologies.

As it was expected, in the isovelocity waveguide with high sound velocity in sediments the deflection of the estimate of *m* from the mode number amounted to a small value. For silt sediments the magnitude of this deflection already depends on the mode number.

As has appeared, the deflection of the estimate is mostly affected by inhomogeneities of the water layer of the waveguide. For the basement media, from sand to media with larger density and sound speed, the difference is practically undetectable. That is, the sound speed profile in water exerts the more influence on the deflection of estimate. The large sound velocities in sediments make the dispersion dependences more close to isovelocity ones. It should be mentioned that the real waveguide was close to the isovelocity one and slightly adjoined to the bottom, however the deflection of *m* differed from the estimates for the model hydrology № 1. Moreover, only for the real hydrology, the estimates of deflection of *m* (from the mode number) qualitatively corresponded to the experimental estimates [7]. That is, the application of the proposed approach for analysis and reconstruction of the bottom characteristics is especially effective in the case of a weak difference of the waveguide parameters from the isovelocity waveguide.

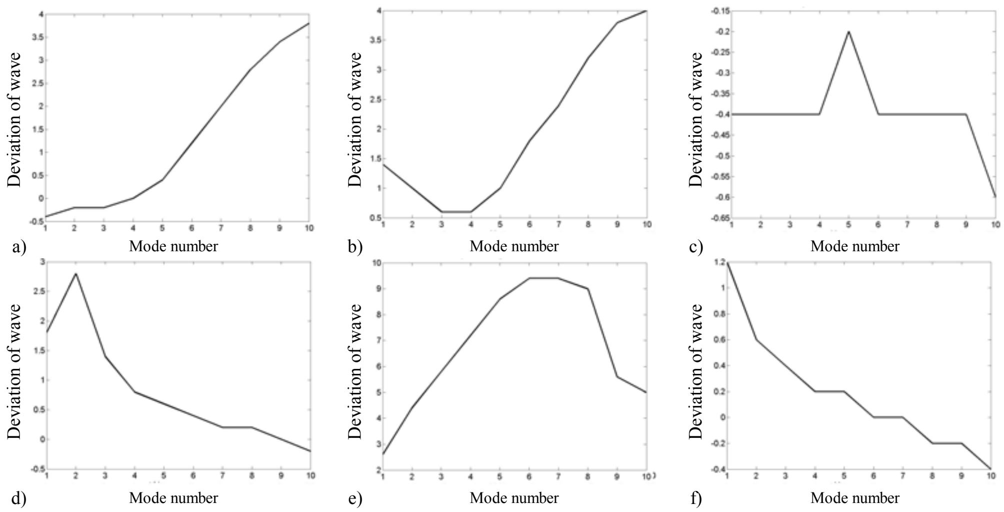

Fig 4. Deviation of the estimation of *m* from mode number at MSD for various hydrologies. Isovelosity waveguide, sediment – mud (a), experimental waveguide, sediment – mud (b), isovelosity waveguide, sediment – limestone (c), close to bottom waveguide, sediment – sand (d), close to surface waveguide, sediment – mud (e), experimental waveguide, sediment – basalt (f),

The carried out analysis has shown, that by determining of maximal correspondence of the dispersion dependences for the real waveguide and the model Pekeris waveguide, it is possible to reconstruct characteristics of the water layer in the shallow waveguide. It turned out also, that determining of sediment characteristics by analysis of the dispersion parameters is practically impossible when the sound speed in bottom substantially exceed the sound speed in water. At the same time, the further study of possibilities of analytical dependences (such as (2)) in application to the MFP can both simplify the signal processing and promote the inverse problem solving for reconstruction of medium characteristics.

REFERENCES

1. Katsnelson B.G., Petnikov V.G. Acoustics of the shallow sea // Moscow, Nauka. 1997. 191p. (In Russian).
2. Borodina E.L., Khilko A.I., Stromkov A.A. Coherent Structure of Broadband Pulse Signals in the Shallow Sea. // The Formation of Acoustical Fields in Oceanic Waveguides. Nizhny Novgorod. 1997. (In Russian).
3. Brekhovskikh L.M. Waves in stratified mediums // M. Nauka. 1973. 343 p. (In Russian).
4. Zverev V.A., Salin B.M., Stromkov A.A. Determination of the mode composition of the sound field with a single-point reception in a shallow sea // Acoustical Physics, V. 51, N2, 2005, pp. 175-181.
5. Hamilton E.L. Geoacoustic modeling of the sea floor // J. Acoust. Soc. Am. V.68, pp. 1313-1336 (1980).
6. Rogers A.K., Yamamoto T., and Carey W. Experimental investigation of sediment effect on acoustic wave propagation in the shallow ocean // J. Acoust. Soc. Am. V. 93 (4), 1747-1761.
7. Zverev V.A., Stromkov A.A., Khil'ko A.I. Selection of modes in the shallow sea using the vertical arrays // Acoustical Physics. V. 52, 2006 (in press).