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ACOUSTIC INTERFERENTIAL DIAGNOSTICS OF THE OCEAN

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Method of the acoustic interferential diagnostics of the ocean is considered as being applied to the solution of two problems – investigating the hydrophysical fields (environmental diagnostics), and defining the structure of the acoustic field of the wide-band sources in the ocean waveguides (sensing of the acoustic field). It is shown the possibility to solve these problems on the basis of using the relation of parameters of interferential two-dimension spatial-frequency distribution of the acoustic fields energy in the ocean with the hydrophysical characteristics of the environment.

Investigation of low- frequency range during the last decades allowed to approach solution of the problems of studying large-scale processes in the ocean by methods of acoustic monitoring [1]. The acoustic waves of the frequencies of ~300 Hz and lower are capable to propagate to the distances bounded by the sizes of the oceanic basins. The acoustic model of the ocean at low frequencies presents itself a "fine" two-dimension waveguide its length making ~10^3 - 10^4 of its thickness, which is ~10- 10^3 of the waves length of the acoustic radiation. This model of the acoustic basin from the point of view of the wave field formation in it is analogues to the model of a fine film or fine plate in the optics. Due to the interference, the white light source "colors" the films with all colors of the rainbow. The interference phenomenon in fine films, plates, lenses is widely used for high-precision diagnostics of the surfaces and internal structure of these objects. Naturally, with the acoustic waves propagation in the ocean, the interference phenomena may be similarly used for diagnostics of the water environment and its margins. Phase relations of the acoustic waves in the ocean are quite sensitive to small changes of the refraction index in the environment, due to this, it appears the possibility to construct the system of diagnostics for non-homogeneities and dynamics of the water environment. A necessary condition for realization of this possibility is conservation of the acoustic waves coherency at large distances, and the availability of the method for *in situ* observations which fits adequately. Real possibility of observing and registering the effects of the acoustic waves interference in the ocean, the so-called fine interference structure, has been confirmed experimentally. The main regularities of its formation [2-4] have been studied. The paper shows that the methods developed in the given studies, i.e. the methods of the acoustic interference, provide new possibilities of the remote sensing of the ocean.

Interferometry methods can be used for the problems of getting (by means of acoustics) the data on hydrophysical characteristics of the ocean environment and their temporal and spatial variations, i.e. for solving the tomographic problems. Similar methods can be also used for solving the problems of studying the ocean as the system of data transfer to the large distances , as well as in solving the applied problems of hydroacoustics. Both ones are based on measuring the characteristics of the spatial-frequency distribution of the acoustic field energy induced by the sound interference in the water environment.

Environmental Diagnostics

The intensity of the sound field of the point source in the hydroacoustic waveguide may be presented as the sum of two members. The first member corresponds to the energetic composition of the waves composing the total field, the second member is interferential:

$$H(w,r,z,z_1)=\sum_{m=1}^{M} A_m(w,r,z,z_1)A_n(w,r,z,z_1)\exp[i y_{mn}(w,r)] \quad (1)$$

here $A_m(\ldots), A_n(\ldots)$ - amplitudes of interferating waves of m,n; $y_{mn}(w,r)$ – phase difference of interferating waves of numbers m,n; w – frequency, r,z – coordinates of the observation point; $0,z_1$ – source coordinates.

Phase $y_{mn}(w,r)$ near to some point w_0, r_0 may be presented as [4]:

$$y_{mn}(w',r') = y_{mn}(w_0,r_0) + u_{mn}w' + v_{mn}r' \qquad (2)$$

where $u_{mn} = \frac{\partial y_{mn}}{\partial w} + \frac{\partial^2 y_{mn}}{\partial w^2}\frac{w'}{2} + \ldots;\quad v_{mn} = \frac{\partial y_{mn}}{\partial r} + \frac{\partial^2 y_{mn}}{\partial r^2}\frac{r'}{2} + \ldots;\quad w' = w - w_0;\ r' = r - r_0$.

In mode presentation of the field:

$$y_{mn}(w,r) = c_{mn}(w)r,\ u_{mn} = r\left.\frac{\partial c_{mn}(w)}{\partial w}\right|_{w_0} + r\left.\frac{\partial^2 c_{mn}(w)}{\partial w^2}\right|_{w_0}\frac{w'}{2} + \ldots,\quad v_{mn} = c_{mn}(w), \qquad (3)$$

where $c_{mn} = c_m(w) - c_n(w)$ – difference of longitudinal wave numbers of the modes of m,n numbers.

In the ray presentation of the field:

$y_{mn}(w,r) = w\,t_{mn}(r)$, where $t_{mn} = t_m - t_n$ – time of signal propagation along the rays m,n.

Thus, being limited by two members of decomposition we get:

$$u_{mn} = t_{mn}(r_0),\ v_{mn} = w\left.\frac{\partial t_{mn}(r)}{\partial r}\right|_{r_0} + \frac{r'w}{2}\left.\frac{\partial^2 t_{mn}(w)}{\partial r^2}\right|_{r_0} + \ldots. \qquad (4)$$

On the basis of expressions (1) and (2) the interferential structure of the field can be presented as the sum of the periodic two-dimension structures:

$$H(w,r,z,z_1) = \sum_{m=1}^{M} A_m(w,r,z,z_1)A_n(w,r,z,z_1)exp[i(u_{mn}w' + v_{mn}r' + y_{mn}(w_0r_0))]; \qquad (5)$$

Proper frequencies of the structure in correspondence with formulas (3) will have the values:

$$u_{mn} = r\frac{\partial c_{mn}(w)}{\partial w} = \frac{r}{c_{\text{ãð},m}(w)} - \frac{r}{c_{\text{ãð},n}(w)} \qquad (6)$$

$$v_{mn} = c_{mn}(w) = w\left[\frac{1}{c_{\text{ô},m}(w)} - \frac{1}{c_{\text{ô},n}(w)}\right] \qquad (7)$$

where $c_{\text{ãð},m(n)}(w)$ – group velocity of $m(n)$ modes correspondingly,

$c_{\text{ô},m(n)}(w)$ – phase velocities of $m(n)$ modes.

So, u_{mn} – travel time difference for modes propagation of numbers m,n from the source to the point of receiver. Parameter $c_{\text{ãð},m(n)}(w)$ is conditioned by the characteristics of the hydroacoustic waveguide: thickness of the water layer, acoustic properties of the ground, vertical profile of sound velocity in the layer.

Proper frequencies of the structure in correspondence with formulas (4) in the approximation of geometric acoustics will possess the following sense:

u_{mn} – relative delays of signals by m,n rays;

v_{mn} – velocity of relative delays variations by m,n rays versus distance r.

As an example, let's consider the waveguide with the deepened axis, in which the vertical profile of sound velocity is given by the ratio:

$$c(z) = \begin{cases} \left(1/c_0^2 - qz\right)^{-1/2} & 0 < z < h \\ \left(1/c_0^2 - q'z\right)^{-1/2} & -h' < z < 0 \end{cases} \qquad (8)$$

where c_0 – sound velocity on the channel axis; q, q' – gradients of sound velocity higher and lower the channel axis, correspondingly. For such waveguide [5]

$$c_m(w) \cong \left[(w/c_0)^2 - w^{4/3}\left(m - \frac{1}{2}\right)^{2/3} \frac{2}{c_0} m \right]^{1/2}, \qquad (9)$$

where $m = \frac{c_0}{2}\left(\frac{3}{2}\frac{p}{1/q + 1/q'}\right)^{2/3}$.

As in formula (9) the second member is significantly lower than the first one, then:

$c_m(w) \cong w/c_0 - w^{1/3} m^{2/3} \frac{c_0}{2}\left(\frac{3}{2}\frac{p}{1/q + 1/q'}\right)^{2/3}$, then $v_{mn} = c_{mn}(w) \cong \frac{c_0 w^{1/3}}{2}\left(\frac{3}{2}\frac{p}{1/q + 1/q'}\right)^{2/3}\left(m^{2/3} - n^{2/3}\right)$

$$u_{mn} = r\frac{\partial c_{mn}(w)}{\partial w} \cong \frac{r c_0 w^{1/3}}{2}\left(\frac{3}{2}\frac{p}{1/q + 1/q'}\right)^{2/3}\left(m^{2/3} - n^{2/3}\right).$$

It is obvious, that the proper frequencies of the interferential structure are conditioned by the parameters of the vertical profile of sound velocity in the environment, i.e. by the values of c_0, q, q'. These parameters variations will lead to the changes of the proper frequencies of u_{mn}, v_{mn} structure.

The problem of measuring the proper frequencies u_{mn} and v_{mn} can be solved by way of two-dimension spectral analysis of the interferential structure $H(w, r)$, i.e. by way of measuring the extremums frequencies of the integral:

$$B(u, v, w_0, r_0) = \int_{w_0 - \frac{\Delta w}{2}}^{w_0 + \frac{\Delta w}{2}} \int_{r_0 - \frac{\Delta r}{2}}^{r_0 + \frac{\Delta r}{2}} H(w, r)\, e^{-i(uw + vr)} dw\, dr \qquad (10)$$

For more precise determination of proper frequencies of the structure in the wave-guides with the dispersion, it is necessary to consider the presence of the second member in formula (3) for $u_{mn}(w)$ in the integral reformation (10).

In case of classical problem of the acoustic tomography of the ocean [1], the initial data in measurements are arrival times of the rays from the source to the receivers. The interferential approach allows to operate with the values of relative delays by the rays (4). The procedure of determining these delays is performed with the help of the integral operation (10). Algorythm (10) possesses some positive properties: increased noise immunity at the expense of spatial averaging, excluding the errors in the rays identification, possibility of measuring the delays with the presence of dispersion in the environment.

In practice, obtaining the interferential structures $H(w, r)$ is carried out with the help of the towered impulse sources of large intensity in the studied water area, where the receiving stationary systems are deployed. Spatial distribution of these systems and the track of the source are chosen with regard to the problem stated for the experiment. To investigate the mesoscale non-homogeneities it is necessary to place the stationary receiving systems in the water area with linear sizes of more than 100 km. The routes of the emitter movement should significantly exceed the spatial periods of the interference. For investigating the dynamics of the environment non-homogeneities it is needed repeated source passing along the given track.

We should say, that the environment investigation developed on this basis may be applied to the studies on seismic profiling of the ocean bottom structures.

Diagnostics of the Acoustic Fields

The given paper pays attention to the ideological grounds and the possibility of developing the experimental studies of fine interferential structure of the acoustic fields in the ocean, its temporal stability, spatial-temporal dynamics and destruction. The basis for the present publication are studies [2-4]. The value of the proposed method is that the measurements of parameters of the fine interferential structure of the field are carried out by way of measuring the field characteristics averaged in space and frequency.

Let's consider the "hologram" of the acoustic field intensity obtained by way of registering the spectrum of the received signal during the movement of the wide-band source along the linear track:

$$G_{\grave{O}}(w, r(t), t) = F_T(w, t)H(w, r) + N_T(w, t) \qquad (11)$$

here $F_T(w,t) = \left| \int_t^{t+T} f(t')e^{-iwt'}dt' \right|^2$ – spectral density of the emitted signal power $f(t)$ obtained with the sliding averaging T. The signal is determined in the frequencies band Δw. Let's consider, that $T >> 2p/\Delta w$, signal is stationary. In this relation, further on, the dependence on t in G_T, F_T, N_T functions is omitted.

$G_{\grave{O}}(w, r(t), t) = \left| \int_t^{t+T} g(t', r(t))e^{-iwt'}dt' \right|^2$ – spectral density of the received signal power $g(t, r(t))$

$H(w, r) = \left| \int_0^{\infty} h(t, r(t))e^{-iwt}\,dt \right|^2$ – transmitted characteristics of the environment, $h(t)$ – response of the environment on the impulse effect.

$N_T(w, t)$ – spectral density of the ambient noise power.

The aim of the acoustic field diagnostics is measuring the transfer characteristics of the environment $H(w, r)$ and its properties.

Point- by- point measuring $H(w, r)$ through the values of $G_{\grave{O}}(w, r(t), t)$ is impossible due the non-controlled factors influence on the measurements for the time of measuring *T*. At monotonous changing the distance with the constant velocity it is possible excluding of the main preventing factors.

The repeated processing of the hologram (11) allows to get the data on parameters of the fine interferential structure.

Two-dimension spectrum of hologram is:

$$\Phi(u, v) = \int_{\Delta w}\int_{\Delta r} G_T(w, r)e^{-i(wu+rv)}dw\ dr\ , \qquad (12)$$

u, v – "frequencies" of the oscillations of spectral density of the power along the frequency and distance axes.

The above said (2) provides the following:

$G_{\grave{O}}(w, r) = F_T(w)H_0(w, r) + F_T(w)H(w, r) + N_T(w)$, where $H_0(w, r) = \sum_{m=1}^{M} A_m^2(w, r)$,

$H(w, r) = \sum_{m,n=1}^{M} A_m(w, r)A_n(w, r)e^{iy_{mn}(w, r)}$.

We are interested in the interferential member $H(w, r)$.

Then: $\Phi_H(u, v) = \int_{\Delta w}\int_{\Delta r} H(w, r)e^{-i(wu+rv)}dw\ dr$.

This integral has been considered in the first part of the paper. Let's say that the measuring of this integral allows to define the spectrum of modes beats, or the spectrum of differences of delays in the signal, proper frequencies of the waveguide.

Spatial dependence relative to the arrival time of signals may be obtained through the procedure of sliding Fourier analysis of the hologram interference along the frequencies axis with the distance scanning $\Phi_1(u, r) = \int_{\Delta w} G_T(w, r)e^{iwu}dw$.

Dispersion characteristics of the environment are experimentally determined by way of sliding Fourier analysis with the distance averaging and the frequency scanning.

$$\Phi_2(w,n) = \int_{\Delta n} G_T(w,r) e^{irn} dr \ \cdot$$

The report presents the results of the experimental studies of fine interferential structure of the acoustic fields at of low frequencies in various areas of the World Ocean.