# AMBIENT NOISE ENERGY MOTION IN THE NEAR-SURFACE OCEAN LAYER

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ABSTRACT. This paper examines the energy properties of the ambient dynamic noise in the near-surface ocean layer to the depth of 1000 m (above the underwater sound channel axis) over the frequency range of 200-800 Hz. It is shown that noise anisotropy in the vertical plane is due to the energy flux of the surface-to-bottom direction; the noise anisotropy in the horizontal plane is associated with surface waves propagation direction and is due to the horizontal noise energy flux; the vertical and horizontal energy fluxes are noncorrelated.

A mechanism of the horizontal energy flux formation induced by scattering of the ambient noise primary fields on a rough ocean surface is proposed.

The investigation technique is based on simultaneous measurement of pressure $p(t)$ and the particle velocity components $V_X(t)$, $V_Y(t)$ and $V_Z(t)$ at a point of the acoustic field and their subsequent statistical cross-analysis.

The studies have been conducted in the Pacific ocean and its marginary seas as well as in the Indian ocean. The detected properties are characteristic of deep open water areas of seas and oceans.

## INTRODUCTION

The ambient noise acoustic field can be represented in the general case by the superposition of three fields, namely: active, reactive and diffuse. The active field is a running wave field describing energy transfer in the oceanic waveguide. Reactive field is the standing wave field characterizing the energy accumulated by the field in the waveguide. The diffuse field is the field of statistically independent sources of equivalent power symmetrically arranged in space relative to the measurement point whose energy as well as the energy of the reactive field is associated with the waveguide and is not transferred in space. The superposition of the active and reactive fields represents the anisotropic part and the diffuse field the isotropic part of the acoustic field. The sum of the anisotropic and isotropic components represents the total field of the ambient noise.

The correlation of the active, reactive and diffuse components in the total field is defined from the cross-analysis of the four field components: acoustic pressure $p(t)$ and three orthogonal particle velocity components $V_X(t)$ , $V_Y(t)$ and $V_Z(t)$ measured simultaneously at the same point of the field.

The components of the real part of the energy flux density vector responsible for the energy transfer are written in the familiar form

$$I_X = \frac{1}{2}\,\mathrm{Re}(pV_X^*)$$

$$I_Y = \frac{1}{2}\,\mathrm{Re}(pV_Y^*)$$

$$I_Z = \frac{1}{2}\,\mathrm{Re}(pV_Z^*)$$

where $V_X^*$, $V_Y^*$, $V_Z^*$ indicate the complex conjugates of $V_X$, $V_Y$, $V_Z$.

The components of the imaginary part of the energy flux density vector

$$Q_X = \frac{1}{2}\,\mathrm{Im}(pV_X^*)$$

$$Q_Y = \frac{1}{2}\,\mathrm{Im}(pV_Y^*)$$

$$Q_Z = \frac{1}{2}\,\mathrm{Im}(pV_Z^*)$$

characterize the power per unit area accumulated by the field.

The description of the field in the frequency region includes the cross-analysis of the random processes $p(t)$, $V_X(t)$ , $V_Y(t)$ ; $V_Z(t)$

- autospectra and cross-spectra:

$$S_{p^2}\,,\ S_{V^2}\,,\ S_{pV_X}\,,\ S_{pV_Y}\,,\ S_{pV_Z}\,,\ S_{V_XV_Y}\,,\ S_{V_XV_Z}\,,\ S_{V_YV_Z}$$

- the usual one-point coherence functions

$$\gamma_{ij}^2(f) = \frac{|S_{ij}(f)|^2}{S_{ii}(f)\cdot S_{jj}(f)} \quad \text{where } i,j = p, V_X, V_Y, V_Z \ ; \text{ and } i \neq j$$

- phase spectra

$$\varphi_{pV_I}(f) = \mathrm{arctg}\left| Im(pV_I^*) / Re(pV_I^*) \right|$$ , where $I = X,Y,Z$

The spectral diffuse field density $S_{p^2}^{dif}(f)$ is determined as the spectral density difference of the total $S_{p^2}^{tot}(f)$ and anisotropic $S_{p^2}^{an}(f)$ fields[1]

$$S_{p^2}^{dif}(f) = S_{p^2}^{tot}(f) - S_{p^2}^{an}(f)$$

## 1. ANALYSIS OF EXPERIMENTAL DATA

Consider the ambient dynamic noise energy properties typical for deep open water areas of seas and oceans. The measurements were conducted in the layer adjacent to the ocean surface (at depths from 100 to 1000 m) above the underwater sound channel axis. The areas of studies were the Pacific ocean and its marginal seas and the Indian ocean. The measurements were carried out at the near-surface wind speeds of 1-12 m/s. The noise properties in question correspond to the steady-state surface roughness, provided that the near-surface wind speed, wind waves and swell propagation directions differ by not more than 15°.

To analyse the noise, we shall use the common one-point coherence function $\gamma_{ij}(f)$ ; $i,j = p, V_X, V_Y, V_Z$ ; $i \neq j$ , phase spectra $\varphi_{ij}(f)$ , $i,j = V_X, V_Y, V_Z$ and the algorithm of calculating the diffuse field spectral density level

$$S_{p^2}^{dif}(f) = S_{p^2}^{tot}(f) - S_{p^2}^{an}(f)$$

Present the results of noise measurements carried out in the South-China sea. Conditions of the experiment are as follows: depth - 3600 m; the underwater sound channel axis lies at a depth of 1200 m; the near-surface sound speed is higher than the near-bottom sound speed; wind speed - 12 m/s; steady-state surface roughness, swell; wind, surface waves and swell directions coincide; measuring devices (two combined modules) are mounted at 250 and 500 m depths; the directions of the combined module axes $X$ coincide with surface wave propagation direction; the combined module axes $Z$ are vertical and directed from surface to bottom.

The measuring facilities and technique are described in [1,2].

Fig. 1 presents coherence functions and their respective phase spectra for the measurement depth of 250 m.

From Fig. 1 it can be seen that the coherence functions and phase spectra for the orthogonal $X$ , $Y$ and $Z$ directions depend on frequency differently. Consider the frequency range of 200-600 Hz in which the distant shipping noise can be neglected.

depth. E. g. in the South-China sea between the depths of 250 and 500 m over the frequency range of 400-600 Hz the energy flux level variations made up (-1.37 ± 0.20) dB for the vertical and (+1.62 ± 0.20) dB for the horizontal one. The variation of the noise energy density level amounted to (+0.42 ± 0.40) dB, which allowed one to consider it to be independent of depth in the range of 400-600 Hz. It should be added here that the vertical and horizontal energy fluxes are noncorrelated [1,3,4].

## 2. A POSSIBLE MECHANISM OF HORIZONTAL DYNAMIC NOISE ENERGY FLUX FORMATION

The coincidence of the directions of surface wind wave propagation and horizontal ambient noise energy flux suggests that the anisotropic properties of surface waves give rise to anisotropic properties of noise field in the horizontal plane.

If the surface wave propagation direction coincides with the positive $+X$ axis direction, the directions $+X$ and $-X$ are physically different. As to $+Y$ and $-Y$ directions, they can be considered in this case physically equivalent on the average. Hence, the resultant energy flux along the $Y$ axis must be equal to zero which is shown by the experiment, i.e. $I_{Y,N} = I_{+Y,N} - I_{-Y,N} = 0$ where $I_{Y,N}$ is the averaged resultant noise energy flux component $\vec{I}_N$ in the $Y$ direction in a certain frequency band; and $I_{+Y,N}$ and $I_{-Y,N}$ are the averaged noise energy flux components in the $+Y$ and $-Y$ directions, respectively.

The resultant noise energy flux along $X$ axis, as it is shown by the experiment, is not always equal to zero

$$I_{X,N} = I_{+X,N} - I_{-X,N} \geqslant 0 \; ; \qquad I_{+X,N} \geqslant I_{-X,N}$$

The obtained experimental result can be accounted for by different scattering of the primary noise field of surface sources in the direction of surface wave motion and against it. The magnitude of the resultant noise energy flux in the horizontal plane $I_{X,N}(f)$ will be proportional to the difference of sound scattering coefficients $\Delta m(\theta)$ in the $+X$ and $-X$ directions and the energy flux value

$$I_{X,N}(f) \sim \Delta m(\theta) I_N(f)$$

where $\theta$ is the local angle of the sound incident on the surface. For a slight sea roughness one can write

$$\Delta m(\theta) \approx (\partial m(\theta)/\partial \theta) \cdot \Delta \theta$$

Using the expressions obtained for $I_{X,N}(f)$ and $\Delta m(\theta)$ and defining

$$I_{X,N}(f)/I_N(f) = \gamma_{pv_x}(f)$$

we write

$$\gamma_{pv_x}(f) \sim \frac{\partial m(\theta)}{\partial\theta}\Delta\theta$$

The dependence of the $\gamma_{pv_x}(f)$ function can be expressed relative to a certain fixed frequency $f_0$

$$\gamma_{pv_x}(f) = \gamma_{pv_x}(f_0)\cdot\left(\partial m_f(\theta)/\partial\theta\right)/\left(\partial m_{f_0}(\theta)/\partial\theta\right)$$

The greatest contribution to the horizontal noise energy flux is introduced by the directions with small slide angles with respect to the undisturbed surface. And if we assume that under such conditions the coefficient $m(\theta)$ is close to the reflection coefficient in the mirror direction at a sliding incidence and a large-scale sea roughness [5], we obtain the following frequency function for $\gamma_{pv_x}(f)$

$$\gamma_{pv_x}(f) = \left(\frac{f}{f_0}\right)^{3/2}\cdot\gamma_{pv_x}(f_0)$$

The equation obtained, as one can see from Fig. 1 (curves 1,7), is in good agreement with the experiment.

## 3. REFERENCES

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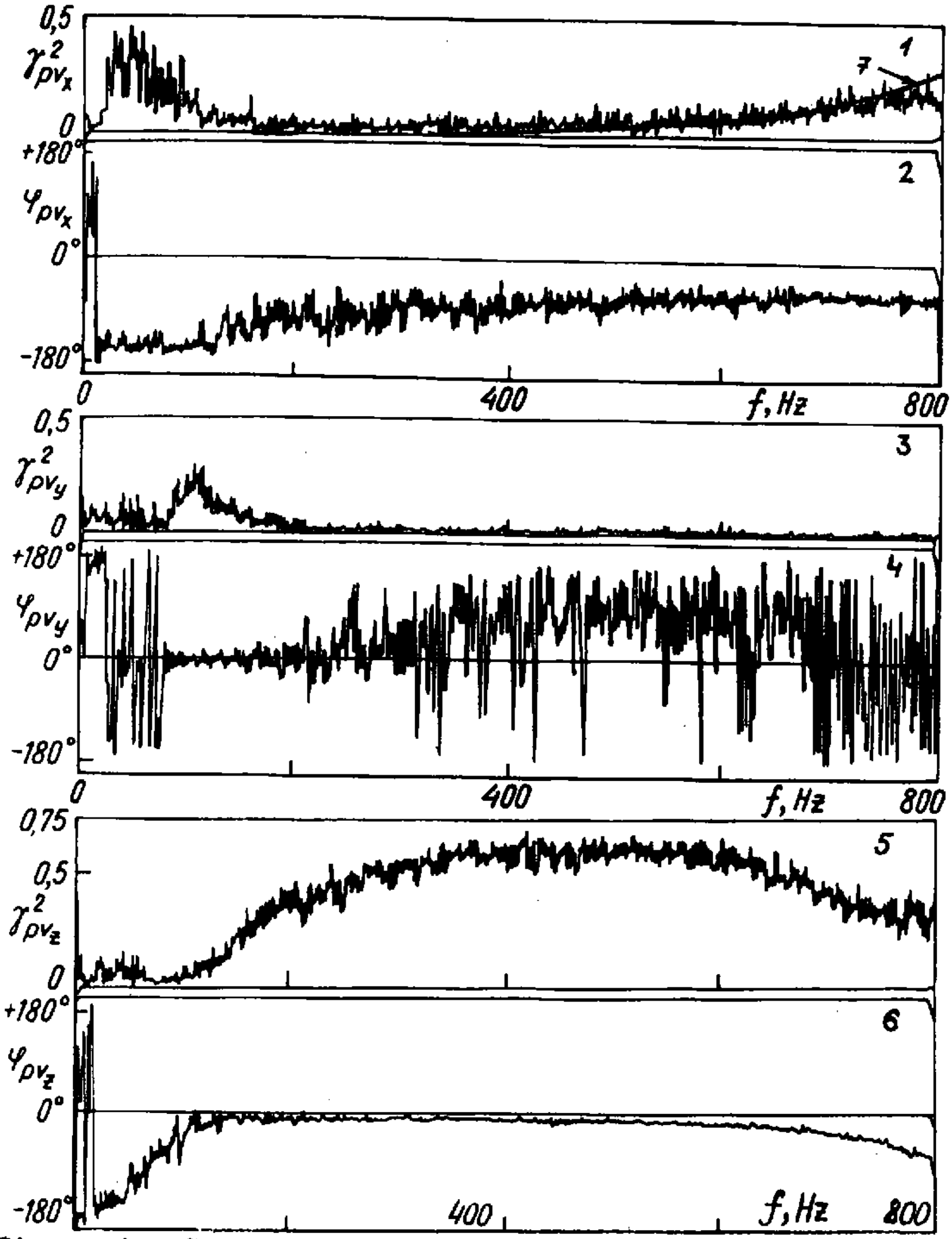


Figure 1. Coherence functions and the corresponding phase spectra. Averaging time is 200 s.
1 - $\gamma^2_{pv_x}$, 2 - $\varphi_{pv_x}$, 3 - $\gamma^2_{pv_y}$, 4 - $\varphi_{pv_y}$, 5 - $\gamma^2_{pv_z}$, 6 - $\varphi_{pv_z}$, and 7 - a theoretical curve $\gamma^2_{pv_x}$.

By the nature of the coherence function and phase difference spectra (Fig. 1, curves 1,2,3,4,5,6) one can draw the following conclusion about the energy properties of the noise fields:

1. The vertical particle velocity component $V_z(t)$ and the acoustic pressure $p(t)$ are in-phased random processes ( $\varphi_{pv_z}(f) \approx 10°$, curves 5,6) and so they form the running wave field in the vertical plane carrying acoustic energy from the noisy surface to the bottom.

2. The horizontal particle velocity component $V_X(t)$ and $p(t)$ (curves 1,2) ( $X$ axis is oriented in the direction of surface wave propagation) at a frequency of 600 Hz and more, have the phase difference of 45° which is the result of statistical averaging of the instantaneous phase difference $\varphi_{pv_X}(f)$ that takes the values in the range 0°-90° with equal probability. The phase difference $\varphi_{pv_X}(f) = 45°$ is due to the appearance of the resultant running wave propagating in the positive direction of the $X$ axis as a result of the superposition of opposing running waves of the noise field along $X$ axis. The resultant running wave originates an energy flux (in the positive direction of $X$ axis) that grows linearly with frequency (curve 1).

3. The phase difference $\varphi_{pv_Y}(f)$ of the horizontal particle velocity component $V_Y(t)$ and $p(t)$ (curves 3,4) ( $Y$ axis is perpendicular to surface wave direction) is about 90° in the frequency range of 350-700 Hz and about 0° at a frequency over 700 Hz. The phase difference $\varphi_{pv_Y}(f) = 90°$ is the average of the random instantaneous value set $\varphi_{pv_Y}(f) = 0°-180°$ arising at an incomplete cancellation of opposing flows; at full cancellation, the instantaneous values of $\varphi_{pv_Y}(f)$ lie in the interval of -180°, +180°, the mean value being 0°.

Thus, in the vertical plane we have an active noise field component, in the horizontal plane, along $X$ axis, - a partially cancelled diffuse field, and along $Y$ axis - a cancelled (diffuse) field. The detected ambient noise energy structure was observed in the near-surface layer of a deep open water area above the underwater sound channel axis up to 1000 m depth at a sea-surface wind speed of more than 2.0-2.5 m/s. At a sea-surface wind speed of less than 2.0-2.5 m/s, the coherence and phase spectra on all of the $X$ , $Y$ , and $Z$ axes are of the same nature as the curves 3,4 in Fig. 1 and the component diffusion makes up 90-95% of the total ambient noise field (at frequencies higher than 200 Hz) [1,3].

The dependence of the vertical and horizontal dynamic noise energy fluxes on the depth of measurement is characterized by the fact that on moving into the ocean waveguide thickness the vertical energy flux becomes scattered (or degraded), while the horizontal energy flux grows with