VORTEX FEATURES OF ACOUSTIC INTENSITY VECTOR IN THE SHALLOW WATER

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The vortex structure of acoustic intensity vector in the shallow water depending on a distance and frequency emitting was researched basing on the natural in-situ experiment. The experiment was fulfilled using the combined acoustic receivers in the Peter the Great Bay in the Japanese Sea. When axes x and y of rectangular system of coordinates being located in horizontal plane of the combined receiver, axis z was directed from surface to bottom. The receiver was submerged to ~70 m depth at the site depth of ~120 m; sound velocity on the surface was higher than that of the bottom's one. To determine the vorticity there were calculated three components of rotor of intensity vector then, their histograms of distribution of probability density were plotted. In the work there were presented distribution histograms of the vorticity probability density of intensity vector for 110 Hz frequency under the different distances between source and receiver within ~1000–5000 m. In the case of single source the highest density of probability corresponds to magnitude of ±1 for x- and y- norm components of rotor and 0 – magnitude for its z-component. As follows from the experiment the steady vorticity of acoustic intensity vector was observed along the entire distance (~4000 m) from source to receiver. The described mechanism of acoustic intensity transfer opens new possibilities in the research of acoustic features in the shallow water. The fixed vortex structures pose an interest as for physical acoustics, as for applied challenges of undersea acoustics.

INTRODUCTION

The vortex structures of acoustic intensity in the aeroacoustics has been known since the 80-es years of last century [1]. Vortices in the reciprocal flows of elastic energy density in the solid body has been known either [2]. In the natural marine environment the vortices of acoustic intensity were revealed in the shallow water by the authors of presented work [3–5]. Fundamentals of given phenomenon consist of $\mathrm{rot}(p\vec{V}^*) \neq 0$, namely:

$$\mathrm{rot}(p\vec{V}^*) = p\,\mathrm{rot}\vec{V}^* + [\mathrm{grad}p \times \vec{V}^*] = [\mathrm{grad}p \times \vec{V}^*], \text{ because } \mathrm{rot}\vec{V}^* = 0 \tag{1}$$

Equation (1) looks like:

$$\begin{gathered} \mathrm{rot}(p\vec{V}^*) = -2\omega\rho_0[\mathrm{Re}\vec{V} \times \mathrm{Im}\vec{V}] = \\ -2\omega\rho_0\left[V_yV_z\sin(\varphi_y-\varphi_z)\vec{i} + V_xV_z\sin(\varphi_x-\varphi_z)\vec{j} + V_yV_x\sin(\varphi_y-\varphi_x)\vec{k}\right] = \\ = -2\omega\rho_0\left(\mathrm{rot}_x p\vec{V}^* + \mathrm{rot}_y p\vec{V}^* + \mathrm{rot}_z p\vec{V}^*\right) \end{gathered} \tag{2}$$

Expression (2) in average is true for occasional stationary tonal signal. The mechanism of vortex formation with components $\pm\mathrm{rot}_x p\vec{V}^*(t) \neq 0$ and $\pm\mathrm{rot}_y p\vec{V}^*(t) \neq 0$ can be explained by the next way. Let's separate into constituent parts the summary actual flux of energy from two sources, namely, into the constituents of every wave from destined *z* direction [6]:

$$I_z = p_1V_1\cos\theta_1 + p_2V_2\cos\theta_2 + [p_1V_2\cos\theta_2 + p_2V_1\cos\theta_1]\cos(\varphi_2-\varphi_1) \tag{3}$$

where p_1, p_2, V_1, V_2 – amplitudes of monochromatic signals of pressure and particle velocity, respectively, θ_1, θ_2, – angles between flows direction and axis *z*, $(\varphi_2\text{-}\varphi_1)$ – phase difference between acoustic pressures of two waves.

The first and the second items in (3) are *z*-components of every energy flux under another flux absence. The third item adds supplementary energy flux along *z* axis when both waves exist simultaneously. Expression (3) depends on the area size through which the summary energy flux is running. If the linear size of this area would be great comparing to wave length, then $<\cos(\varphi_2-\varphi_1)> = 0$. If the linear size of this area would be commensurable or less, than wave length, then, the third item of sum changes its sign (it results into alteration of propagation direction of supplementary energy fluxes). So, the energy running through surface to +*z* direction will be returning into another point of this surface along – *z* direction. This point to the phenomenon when acoustic energy will be propagating along closed contour.

1. THE EXPERIMENT CONDITIONS

The experiments were fulfilled in 2008–2010 in the Peter the Great Bay of the Japanese Sea at the site depth from 30 m to 250 m. In the presented paper we shall describe the results of one of 2008 year's experiments. Plot of the experiment is given in Fig. 1. Research was implemented using combined systems over 5–1000 Hz band of frequency. The distance between moving source of radiation and receiving system was changing within ~1000–5000 m during experiment. Technique of combined vectorial measurements was described in [6].

Measurements of particle velocity of medium particles were accomplished applying the electro-dynamic receiver of particle velocity. A combined receiver was placed in the measuring cigar-shaped module being streamlined and possessing neutral floatage positioned at 70 m depth. Axes *x*, *y* of the combined receiver were directed in the horizontal plane. Axis *z* was arranged vertically and directed from surface to bottom. At the point of acoustic measurements the depth of site was 120 m. The buoy (2, Fig. 1) was submerged to ~55 m depth. In such case the surface sea roughness didn't influence steady work of acoustic system. During experiment the speed of wind was changing within 5–7 m/s, well-developed wind-driven waves. A researched region was the region of intense close navigation. During day and night experiment through all the researched frequencies range, in the most time there were observed noises from a few surface sources located in the researched area as before, as farther than abyss frontier.

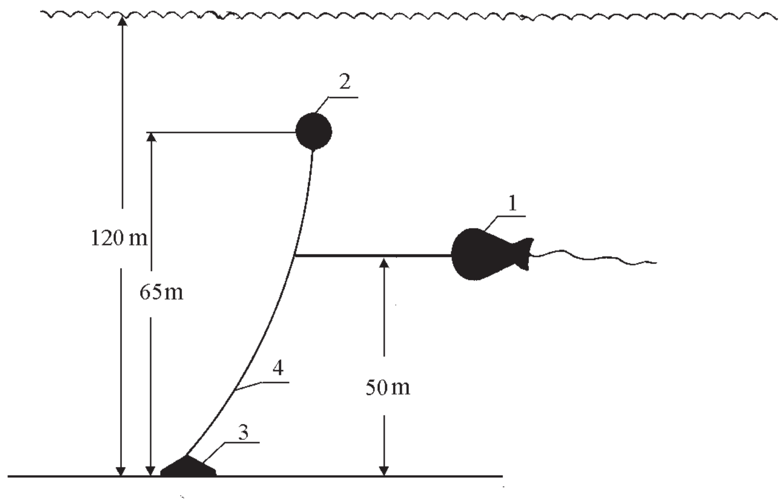

Fig. 1. Scheme of combined measuring system position: 1 – measuring module, 2 – submerged buoy, 3 – bottom anchor, 4 – cable

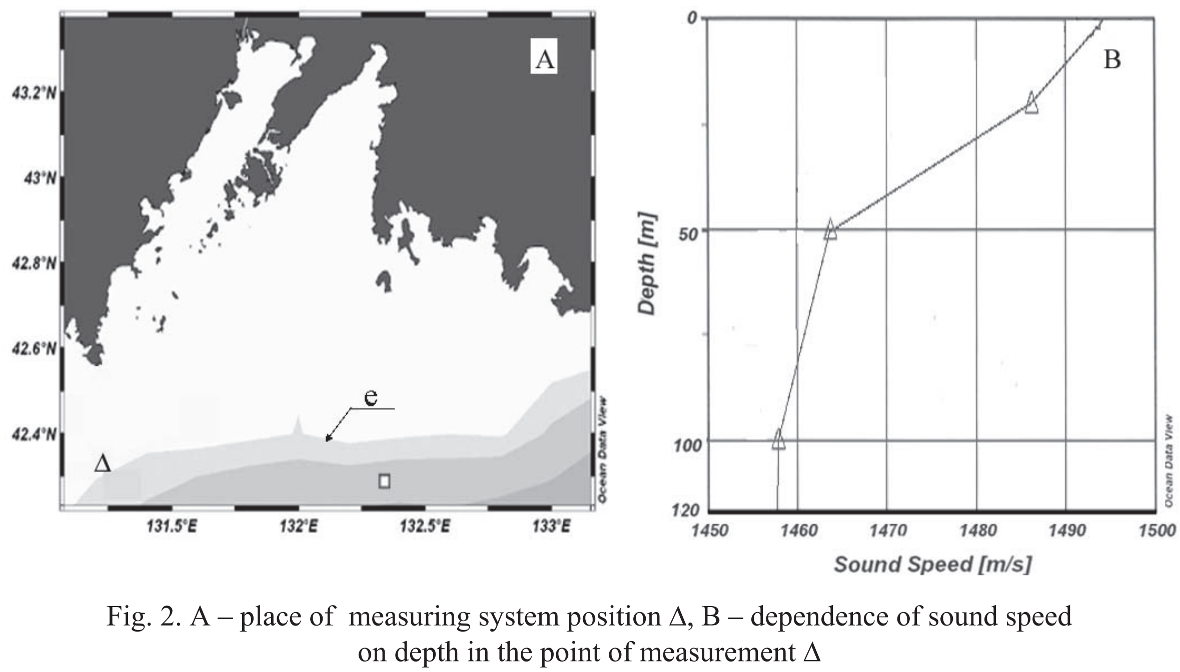

Fig. 2. A – place of measuring system position Δ, B – dependence of sound speed on depth in the point of measurement Δ

The slowly moving vessel of large-capacity that was navigating with constant ~1,5 m/s speed was used as wideband source. The vessel passed by receiving system and changing course with two traverses relatively the receiving system (~1000 m distance) moved away from the receiving system to ~5000 m. All the vessel travel ran in the shallow sea part until the abyss frontier. The site depth above which this vessel traveled was equal to 100–200 m. The bottom there was a smooth flatness being a little slope to the side of abyss frontier. Thus, the experiment conditions respond to the shallow sea parameters. Wave-guides of the shallow sea imply in itself such environment where a bottom type plays significant part in acoustic field formation. General contribution to the acoustic field formation in researched wave-guide was given by the refracted surficially rays being then reflected from bottom. Time of research was October. Installation of the system was made in the vicinity of abyss. The installation plot is marked by Δ sign in Fig. 2A. The abyss is marked by dark tone (e). Dependence of sound speed on depth is presented in Fig. 2B.

2. THE RESULTS OF EXPERIMENT

In the work there were researched vectorial acoustic field of solely moving wideband source. In Fig. 3 there was presented a sonogram of *z*-component of real part in the mutual spectrum $\mathrm{Re}\,S_{PV_z}(f,t)$ that was recorded under the solely moving vessel. Averaging was exponential. Time of averaging was 3 s. Analysis band equaled 2 Hz. Frequency band was 5−800 Hz. During time intervals of 0−600 s and 800−1500 sec two traverses from the vessel passing by were observed.

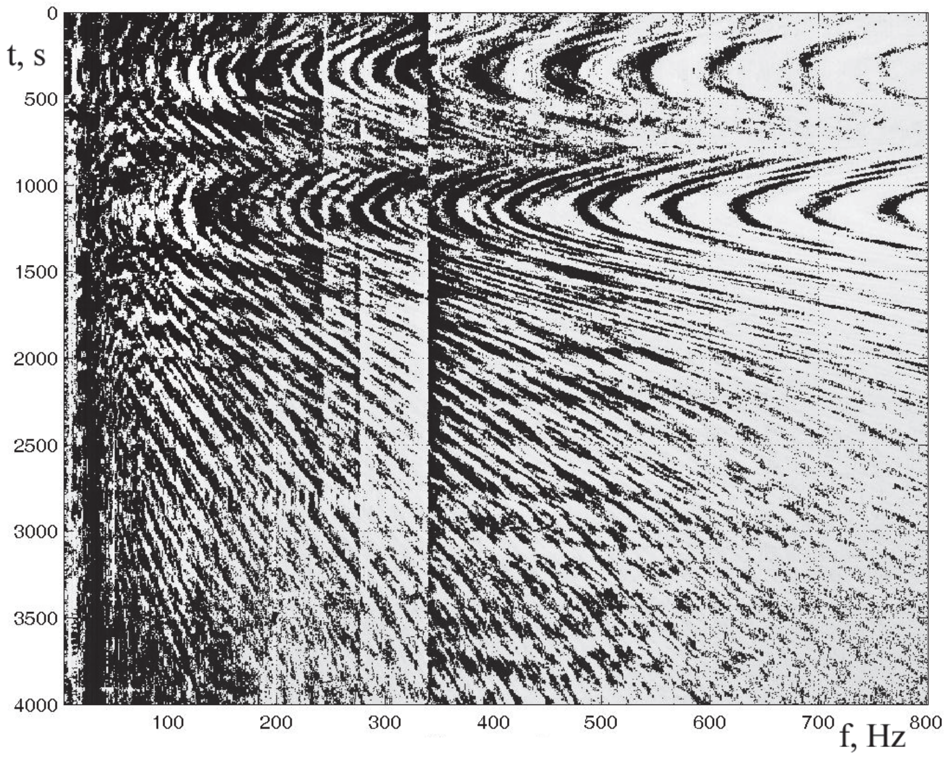

Fig. 3. Sonogram $\mathrm{Re}\,S_{PV_z}(f,t)$

In a black-and-white sonogram the black field means that the vertical component of energy flux density $\mathrm{Re}\,S_{PV_z}(f,t)$ has direction from surface to bottom, the white field is congruent with contrary direction from the bottom to surface. It follows from Fig. 3 that in the point of measurement the moving source creates interferential field where as on time, as on frequency, the vertical *z*-component of density vector of energy flux periodically was changing propagation current that was veering to 180°, i.e. down to bottom and upward to surface. The horizontal components of energy flux density $\mathrm{Re}\,S_{PV_x}(f,t)$ and $\mathrm{Re}\,S_{PV_y}(f,t)$ aren't given because they don't possess the same peculiarities and point to the steady transfer of acoustic energy in horizontal direction.

Let's consider the features of interferential field on frequency f_0 = 110 Hz depending on time (distance) sampling the next magnitudes (Fig. 4): A – spectral density of acoustic pressure $S_{P^2}(f_0,t)$; B – z-component of the real part of energy flux density $\mathrm{Re}\,S_{PV_z}(f_0,t)$; C – polar angle $\theta(f_0,t)$ for the entire vector of energy flux density (intensity vector) $\vec{I}(f_0,t)$.

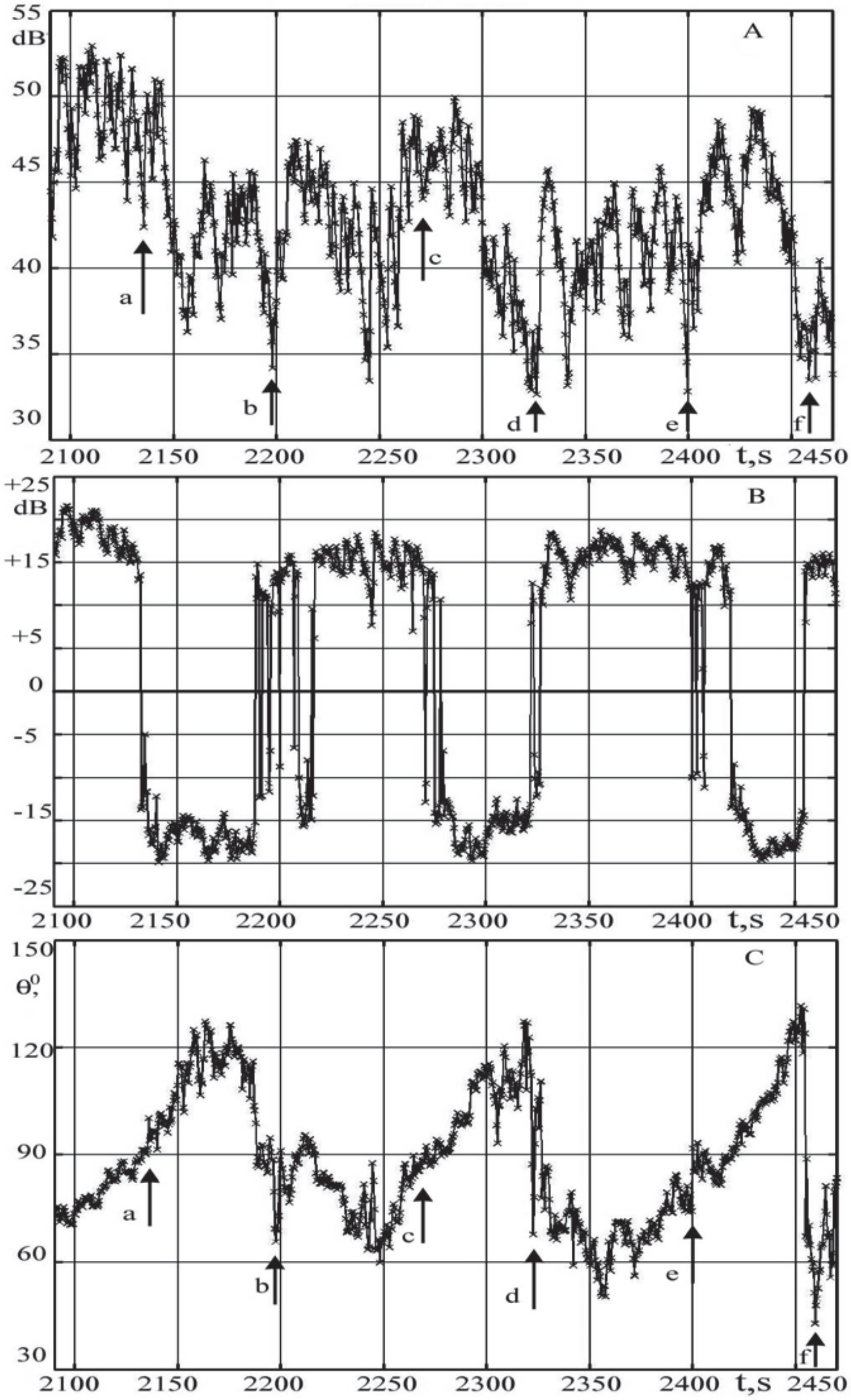

Fig. 4. Dependence on time: A – $S_{P^2}(f_0,t)$ spectral density of acoustic pressure;
B – $\mathrm{Re}\,S_{PV_z}(f_0,t)$ z-component of acoustic intensity; C – θ polar angle of intensity vector $\vec{I}(f_0,t)$, f_0 = 110 Hz. Averaging was exponential, analysis band equaled Δf = 2 Hz., time of averaging was 3 s

In Fig. 4B the next underline captions are introduced. Sign «+» dB corresponds to the energy flux density directed downward (to bottom); «-» dB responds to the energy movement directed from bottom to surface. The chosen parameters tally with 2100–2450 s period of time at Fig. 3 sonogram. Given here period of time matches with distance of 1200–1750 m between the source and receiver. Acoustic pressure (Fig. 4A) fluctuates as a result of multibeam interference. The profound of interferential minimums of acoustic pressure relatively neighboring interferential maximums reaches magnitudes from −5 dB to −15 dB. Let's signify the special points as **a**, **c**, **e** in which $S_{P^2}(f_0,t)$ achieves its relative minimum magnitudes; $\operatorname{Re} S_{PV_z}(f_0,t)$ in the vicinity of these points is veering propagation to ±180°; polar angle $\theta\,(f_0,t)$ in **a**, **c**, **e** points runs without peculiarities through value of θ = 90°, but in the points **b**, **d**, **f** endures 'jump' to angle ~60° (from ~120° to ~60°, Fig. 4C). There should be remarked that at $\theta = 90^0$ vector of intensity $\vec{I}\left\{\operatorname{Re} S_{PV_x}, \operatorname{Re} S_{PV_y}, \operatorname{Re} S_{PV_z}\right\}$ lies in *xoy* horizontal plane, i.e. in the vicinity of points **a**, **c**, **e** $\operatorname{Re} S_{PV_z}(f_0,t)$ = 0. It follows from Fig. 4C that during total sampling the vector of intensity $\vec{I}(f_0,t)$ is changing its direction relatively the horizontal plane. At that while changing the sign of $\operatorname{Re} S_{PV_z}$ from «+» to «-» the vector $\vec{I}(f_0,t)$ is rotating without peculiarities (continuously) (**a**, **c**, **e** points). At changing the sign of $\operatorname{Re} S_{PV_z}(f_0,t)$ from «+» to «-» a 'jump' $\theta\,(f_0,t)$ takes place and vector $\vec{I}(f_0,t)$ by 'jumping' alters its direction (points **b**, **d**, **f**). As a result in the shallow sea waveguide along vertical plane any periodical alternation arises in opposite directions of the energy fluxes on which frontiers vortices of vector of intensity $\vec{I}(f_0,t)$ can arise. Vorticity rate of the intensity vector was being calculated according to equation (2). Phase differences $(\varphi_y-\varphi_z)$, $(\varphi_x-\varphi_z)$, $(\varphi_y-\varphi_x)$ were computed from the mutual spectra of components of particle velocity $S_{V_yV_z}(f_0,t)$, $S_{V_xV_z}(f_0,t)$, $S_{V_yV_x}(f_0,t)$. Frequency was f_0 = 110 Hz, analysis band equaled Δf = 2 Hz, time of averaging was 3 s. Further, there were calculated norm components of rotor of the intensity vector $\operatorname{rot}_x\vec{I}(f_0)$, $\operatorname{rot}_y\vec{I}(f_0)$, $\operatorname{rot}_z\vec{I}(f_0)$ and their histograms of probability distribution were compiled. Time for the histogram collection was 350 s.

In Fig. 5 the histograms of probability density in norm components of the rotor of intensity vector were presented. In Fig. 5A the histogram was compiled for occasional magnitude of *z*-component of intensity vector $\operatorname{rot}_z\vec{I}(f_0)$. Because of average value $<\operatorname{rot}_z\vec{I}(f_0)>=0$ there can be ensured that the vorticity of vector is absent in *xoy* horizontal plane. Vorticity magnitude in the *xoz* and *yoz* vertical planes differs from zero that follows from Fig. 5B, C. So, the current lines on which acoustic energy runs in vortex, lie in the vertical plane where a sonic source and a receiver are positioned. It follows from Fig. 5B, C histograms that probability density of norm magnitudes of vorticity $\operatorname{rot}_x\vec{I} = \pm 1$ and $\operatorname{rot}_y\vec{I} = \pm 1$ differs from zero. Value ±1 indicates to the intervention of vortices opposite directed, at that, as a rule, neighboring vortices have reciprocally contrary directions.

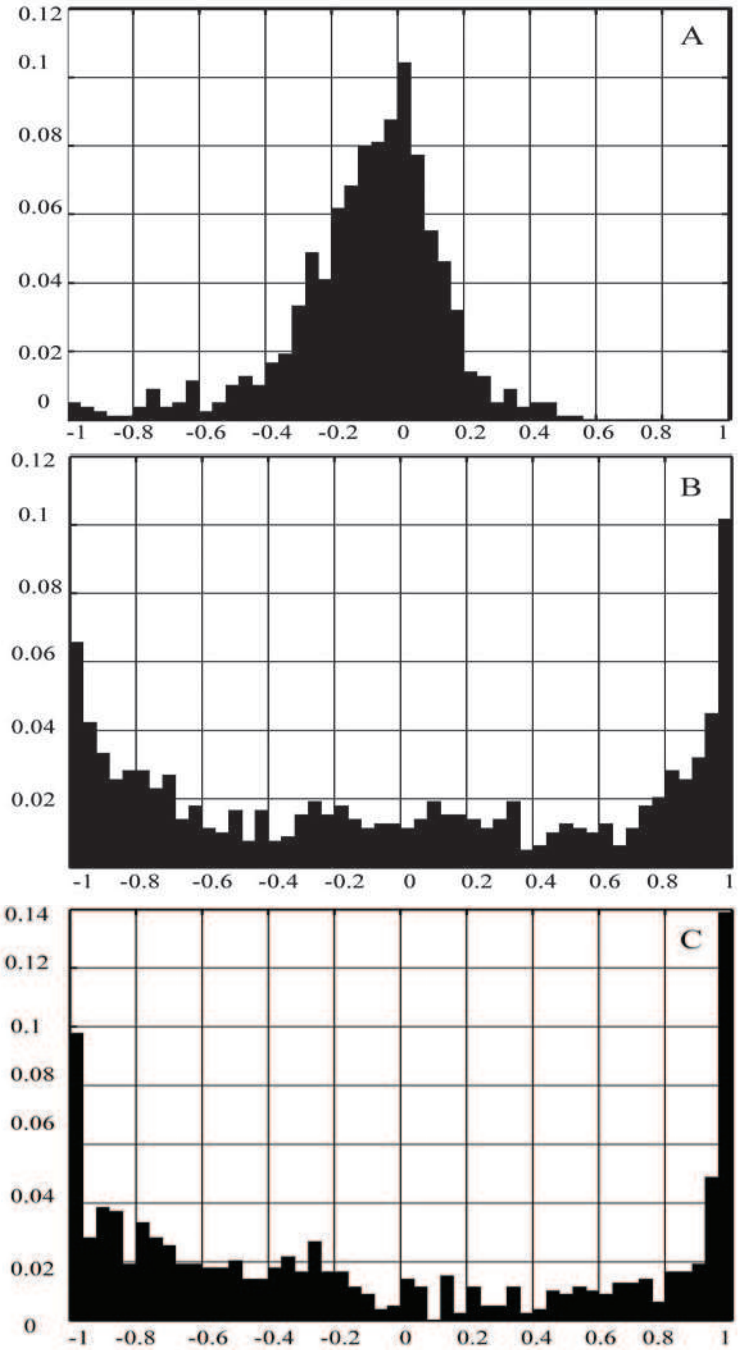

Fig. 5. Histograms of distribution of probability density in the norm magnitudes of variates: A – $\mathrm{rot}_z\vec{I}(f_0)$; B – $\mathrm{rot}_x\vec{I}(f_0)$, C – $\mathrm{rot}_y\vec{I}(f_0)$. Frequency of tonal signal f_0 = 110 Hz band of analysis – 2 Hz, time of averaging – 3 s, time for sampling – 350 s

3. CONCLUSIONS

As a result of acoustic experiment in the shallow sea real waveguide, the vortex nature of vector of acoustic intensity was discovered. Scalar and vector parameters of acoustic field from solely wide-band source were studied at the different distance between the source and combined receiver. It was revealed that in the vertical plane, where a sonic source and a receiver were positioned, the rotor of acoustic intensity had x- and *y*-components that were not equal to zero. Average magnitude of vertical *z*-component of rotor was equal to zero. Thus, there was disclosed that acoustic energy propagates in the shallow sea waveguide through a chain of vortices. The system of vortices is steady and it was observed at ~1000–5000 m distance from source to receiver. This physical phenomenon bears universal nature and must be taken into attention solving fundamental and applied problems of undersea acoustics.

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