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APPLICATION OF LASER-INTERFERENCE METHODS IN HYDROACOUSTIC RESEARCHES

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Results of application laser-interference methods are discussed at research of the nature of hydroacoustic oscillations variations and waves of infrasonic and sound ranges. Coastal laser strainmeters of various variants, laser nanobarographs, laser measuring instruments of hydrosphere pressure variations and laser hydrophones are created on the basis of modern laser-interference methods. Laws of generation, dynamics of oscillations and hydrosphere waves of frequencies wide range and their transformation in the next geospheres are investigated with the help of the given installations. Constructive and technical features of creation bottom laser strainmeters and laser receivers of power type are considered in which basis of construction vector-phase methods lay

More 25 years ago in POI FEB RAS researches on studying of laws of generation and dynamics of oscillations and hydrosphere waves of frequencies wide range and also their transformations in elastic oscillations and waves of an earth's crust, with the help of coastal laser strainmeters of equal and unequal variants have been started. At conceptual stage of research works on research of opportunities coastal laser strainmeters have been executed at registration and direction finding of the various artificial objects located on a shelf on denting and for denting depths [1-4]. Further the cycle of works on studying of transformation laws of superficial standing and progressive sea waves in microseisms of the first and second sort, accordingly [2, 5-7] has been carried out. For the first time in world practice it has been established, that energy of the internal sea waves extending on a shelf of variable depth is transformed basically not in energy of small-scale turbulence as it was considered earlier, and in energy of elastic oscillations of an earth's crust [8]. Afterward on the basis of laser interferometry, methods by remote definition of dynamic characteristics of internal sea waves [2, 9] have been developed. A number of works has been devoted to studying of the energy contribution of surging phenomena, seiches, high tides in microdeformations energy of an earth's crust of transition zone [10-12] as a result of which carrying-out existence of the reversal-barometric effect connected to loading force to an earth's crust of water mass at passage of barometric depressions of various scales through "water-land" interface has been established [13]. Not long ago methods of remote definition of tsunamigenic degree of underwater earthquakes have been developed on the basis of the analysis of the experimental data received at registration of signals of frequencies wide range, connected with tsunamigenic and not tsunamigenic earthquakes, by 52,5-meter laser strainmeter [14, 15].

Let's give some results received at registration by coastal laser strainmeter of seismoacoustic oscillations of an earth's crust which have arisen as a result of transformation of low-frequency hydroacoustic oscillations on "hydrosphere-lithosphere" interface. Low-frequency hydroacoustic oscillations were created in water with the help of various low-frequency hydroacoustic radiators.

At work of low-frequency hydroacoustic radiators in various points of a shelf and for denting area the energy of hydroacoustic oscillations transformed into seismoacoustic energy of a transition zone "hydrosphere-lithosphere" is appreciated [16] . During performance of calculations for a basis the experimental data have been chosen of 1995 resulted in table 1, where : R - distance from a place of radiation up to laser strainmeter; H - depth of the sea in radiation place; h - depth of immersing of a low-frequency hydroacoustic radiator; F - frequency radiated signal; P - the pressure resulted in distance 1 m from the radiator geometrical center; A_1 - average amplitude of the seismoacoustic signal registered by laser strainmeter of unequal-arm type with shoulder length of 52,5 m at work of a low-frequency hydroacoustic radiator in a mode of continuous radiation; A_2 - the "resulted" amplitude to equal radiation pressure of (2,3 kPa) for strainmeter with shoulder length of 52,5 m.

Table 1. The experiment data of 1995.

№ st.	R, km	H, m	h, m	F, HzГц	P, kPa	A_1, nm	A_2, nm
1	16	34	31	32	1,87	0,23	0,28
2	16	35	31	32	2,3	0,30	0,30
3	16	53	31	32	1,9	0,29	0,35
4	16	71	31	32	2,3	1,74	1,74
5	25	106	31	32	1,9	0,51	0,62
6	34	1300	31	32	1,9	0,61	0,74
7	43	2131	31	32	1,9	0,52	0,68

Let's find the relation of an energy stream in Rayleigh wave $\varPhi_r$ to the radiated acoustical power near-surface source P_a for stations №6 and №7, the most corresponding to conditions of the deep sea. Tests of a ground have been taken and analysed in area of carrying out of experiment . According to the analysis the following values of elastic constants for calculation of Rayleigh wave have been accepted: Poisson's ratio - 0.3; speed of transverse waves - 3400 km/s, density of bottom breeds - 2600 kg / m3.

According to [17] we shall write down power near-surface source as:

$$P_a = \frac{4\pi P_m^2}{\rho c}\left(1 - \frac{\sin(4\pi h/\lambda)}{4\pi h/\lambda}\right), \tag{1}$$

where: P_m is the effective acoustic pressure resulted in distance 1 m from the source geometrical center, λ is length of an acoustic wave in water, c is sound speed in water, ρ is density of water.

A stream of energy in Rayleigh wave $\varPhi_r$ we shall calculate under the formula [18]:

$$\Phi_r = \pi R \rho U_x^2(0)\omega c_t^2 \cdot \left[\frac{A_1(\nu)}{2\sqrt{1-\eta_r^2\xi^2}} - \frac{A_2(\nu)}{\sqrt{1-\eta_r^2\xi^2}+\sqrt{1-\eta_r^2}} + \frac{A_3(\nu)}{2\sqrt{1-\eta_r^2}}\right] \cdot \left(\frac{2-\eta_r^2}{2-\eta_r^2-2\sqrt{1-\eta_r^2\xi^2}\,\sqrt{1-\eta_r^2}}\right)^2, \tag{2}$$

where: c_r is Rayleigh wave speed; ν is Poisson's ratio; $A_1(\nu) = 4 + \eta_r^2 - 4\eta_r^2\xi^2$

$$A_2(\nu) = \frac{2\sqrt{1-\eta_r^2\xi^2}\left(\sqrt{1-\eta_r^2}+\sqrt{1-\eta_r^2\xi^2}\right)\left(2+\eta_r^2+2\sqrt{1-\eta_r^2}\,\sqrt{1-\eta_r^2\xi^2}\right)}{2-\eta_r^2};$$

$$A_3(\nu) = \frac{4\left(1-\eta_r^2\xi^2\right)\left(4-3\eta_r^2\right)}{\left(2-\eta_r^2\right)^2};\ \eta_r = \frac{0{,}87+1{,}12\nu}{1+\nu};\ \xi = \sqrt{\frac{1-2\nu}{2(1-\nu)}}.$$

Then, at the account of experimental data of tab. 1, we have: for station № 6 $\frac{\Phi_r}{P_a} = 9.89\cdot 10^{-3}$, for station № 7 $\frac{\Phi_r}{P_a} = 11.07\cdot 10^{-3}$. From the above-stated estimations follows, that about 1 % of the radiated acoustic energy by hydroacoustic radiator is transformed to energy of elastic Rayleigh waves.

Works on studying opportunities of application laser strainmeters and low frequency hydroacoustic radiators have been carried out at realization on frequency about 30 Hz, was towed with small speed on a bay of variable depth. The of tomographic investigations of a bottom of shelf areas of the seas and oceans. In bay Vityaz of sea of Japan the first experimental researches have been carried out. With the help of a boat the low-frequency hydroacoustic radiator working radiator worked in a continuous mode during all towage. Before carrying out of an experiment the task was put by experimental definition of characteristics variations of the radiated signal from depth of radiation place. During processing the received experimental data is established that at growth of sea depth from 20 m up to 29-30 m the amount of the transformed hydroacoustic energy in seismoacoustic one increases almost under the linear law. At the further increase and the subsequent small reduction of depth it is not observed dependences of amount of the transformed energy from sea depth.

With the purpose of studying laws of transformation of seismoacoustic oscillations and waves in hydroacoustic oscillations and waves at sea experimental station of V.I. Ilyichev Pacific Oceanological Institute FEB RAS and in Peter the Great bay of sea of Japan in 2007 has been carried out experiment on generation of seismoacoustic oscillations in an earth's crust by low-frequency seismoacoustic radiator and to reception of the given oscillations by 52,5-meter laser strainmeter on coast, and also the transformed seismoacoustic oscillations in hydroacoustic ones by laser measuring instrument of hydrosphere pressure variations established on a shelf on depth of 27 m.

The low-frequency seismoacoustic radiator is created on the basis of use of the electric motor of the direct current which is carrying out an active role with the task of effort of rotation of a shaft and its frequency, a frequency regulator, the rectifier, the vibrator. The vibrator through flexible connection is connected to the basic electric motor. It is executed on the basis of the passive electric motor in which rotor part is made with displaced center of mass concerning an axis of rotation. The frequency range of oscillations created by seismoacoustic radiator reaches from 2 up to 20 Hz. it can work most intensively on frequencies from 10 up to 20 Hz.

Seismoacoustic oscillations were registered by permanently established 52,5-meter laser strainmeter which optical circuit is constructed on a basis of Michelson interferometer of unequal-arm type. The frequency-stabilized helium - neon laser is used in it as a light source. Used methods of interferometry have allowed to create laser strainmeter having the following characteristics: accuracy of measurement of a site of the earth's crust displacement equal to length of an actuating arm interferometer (52,5 м) - 0,1 nm, frequencies working range - 0-1000 Hz, the dynamic range is practically unlimited at measurement of natural processes of an infrasonic range.

Hydroacoustic oscillations and waves were registered by a laser measuring instrument of which has the following basic characteristics: measurement accuracy of hydrosphere pressure variations at membrane thickness of 0.1 mm is equal 57 μPa a working range of frequencies - from 0 up to 1000 Hz, the dynamic range is practically unlimited, working depths - up to 500 m.

The low-frequency seismoacoustic radiator settled down in 100 m from laser strainmeter under a corner 25^0 concerning its main axis and in 320 m from a laser measuring instrument of hydrosphere pressure variations which has been established on depth of 27 m on a shelf of sea of Japan.

During carrying out of an experiment the frequency of radiated signal varied jumps and smoothly in a frequency range from 14 up to 19 Hz. The radiated signal synchronously was registered by laser strainmetwer and a laser measuring instrument of hydrosphere pressure variations. With the purpose of the analysis we shall choose seven characteristic synchronous sites of records of laser strainmeter and a laser measuring instrument of hydrosphere pressure variations. In table 2 the data of spectral processing of synchronous records of the specified installations are resulted.

Table 2. The data of spectral processing oflaser strainmeter records and a laser measuring instrument of hydrosphere pressure variations.

Frequency, Hz	14,22	14,46	14,87	15,24	15,99	18,50	18,91
Amplitude, nm. Laser strainmeter	57,4	55,3	46,5	67,8	84,0	78,9	51,3
Amplitude, Pa. Laser measuring instrument of hydrosphere pressure variations.	0,74	0,80	0,66	0,74	1,15	1,10	0,74

On the basis of the received experimental data we shall estimate a level of accepted seismoacoustic energy and the hydroacoustic one by laser strainmeter accepted by a laser measuring instrument of hydrosphere pressure variations.

Let's estimate stream density of energy in elastic isotropic medium. According to [19] we shall describe j component of vector of energy stream density of elastic oscillations in isotropic medium:

$$\mathrm{P}_\mathrm{j} = -\sigma_{ij}\dot{u}_i(r,t) \tag{3}$$

where: σ_{ij} - strain tensor generated by an elastic wave, $\dot{u}_i(r,t)$ - is component of a vector of displacement of medium particles under wave action.

In isotropic medium

$$\sigma_\mathrm{ij} = \lambda u_{ii}\delta_{ij} + 2\mu u_{ij}\ ,(4) \tag{4}$$

where: $\mathrm{u}_\mathrm{ij} = \frac{1}{2}(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})$ - deformation tensor.

For acoustic longitudinal waves $\mathrm{u}_\mathrm{ij} = u_{ii}\delta_{ij}$, then

$$\sigma_\mathrm{ij} = (\lambda + 2\mu)u_{ii}\delta_{ij}$$

where: λ, μ - Lamé constants.

j - component of stream density vector

$$\mathrm{P}_\mathrm{j} = (\lambda + 2\mu)u_{ii}\dot{u}_i\delta_{ij}. \tag{5}$$

For an acoustic longitudinal wave in the elastic medium

$$\mathrm{u}_\mathrm{ii} = \frac{1}{2}(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_i}{\partial x_i})$$

$$\mathrm{P}_\mathrm{j} = -(\lambda + 2\mu)\frac{\partial \mathrm{u}_\mathrm{i}}{\partial \mathrm{x}_\mathrm{i}}\frac{\partial \mathrm{u}_\mathrm{i}}{\partial \mathrm{t}}\delta_\mathrm{ij}. \tag{6}$$

For a plane harmonic wave,

$$\mathrm{u}_\mathrm{i} = u_{0j}\sin(k_i x_i - \omega t),$$

$$\frac{\partial u_i}{\partial x_i} = k_i u_{0i}\cos(k_i x_i - \omega t),$$

$$\frac{\partial \mathrm{u}_\mathrm{i}}{\partial \mathrm{t}} = -\omega u_{0i}\cos(k_i x_i - \omega t),$$

$$\mathrm{P}_\mathrm{j} = (\lambda + 2\mu)u_{0j}^2 k_i\omega\cos^2(k_i x_i - \omega t)\delta_{ij}. \tag{7}$$

Average component of stream vector on time

$$\overline{\mathrm{P}}_\mathrm{j} = \frac{(\lambda + 2\mu)}{2}u_{0j}^2 k_i\omega\delta_{ij}. \tag{8}$$

If take into account, that speed of longitudinal elastic waves $\mathrm{c}_\mathrm{l} = \sqrt{\frac{\lambda + 2\mu}{\rho}}$, where ρ - density of breeds, and $\omega = \mathrm{c}_\mathrm{l}k_i$, then

$$\overline{\mathrm{P}}_\mathrm{j} = \frac{1}{2}\rho u_{0j}^2\omega^2 c_l, \tag{9}$$

or

$$\overline{\mathrm{P}}_{\mathrm{j}} = \frac{(\lambda + 2\mu)}{2} \frac{u_{0j}^{2}\omega^{2}}{c_{l}} \delta_{ij}. \tag{10}$$

Average energy density of an elastic wave on time can be written down as:

$$\overline{\mathrm{E}}_{\text{у.в.}} = \frac{\overline{\mathrm{P}}_{\mathrm{j}}}{\mathrm{c}_{l}} = \frac{1}{2}\rho u_{0j}^{2}\omega^{2}. \tag{11}$$

If take into account the diagram of an orientation laser strainmeter,

$$\mathrm{u}_{0\mathrm{jд}} = u_{0j} g(\theta), \tag{12}$$

where: $\mathrm{u}_{\mathrm{ojд}}$ - the measured displacement by laser strainmeter and

$$\overline{\mathrm{E}}_{\text{у.в.}} = \frac{1}{2\mathrm{g}^{2}(\theta)}\rho u_{0j\text{д}}^{2}\omega^{2}, \tag{13}$$

where: $\mathrm{g}(\theta) = \cos(\theta)$

Energy density of a hydroacoustic harmonic wave can be written down as:

$$\overline{\mathrm{E}}_{\mathrm{ac}} = \frac{P_{0}^{2}}{2\rho_{в} c^{2}}, \tag{14}$$

where: P_0 - measured by laser measuring instrument of hydrosphere pressure variations hydroacoustic pressure, ρ_{w} - water density, c - sound speed in water.

We shall find the relation of density of hydroacoustic energy to density of elastic energy $\frac{\overline{\mathrm{E}}_{\text{ак}}}{\overline{\mathrm{E}}_{\text{у.в.}}}$ at, $\theta = 25^{0}, \rho = 2000\,\mathrm{kg/m^{3}}$. In table 3 these ratios for all cases described in tab. 2 are resulted.

Table 3.

Frequency, Hz	14,22	14,46	14,87	15,24	15,99	18,50	18,91
$\frac{\overline{\mathrm{E}}_{\mathrm{ac}}}{\overline{\mathrm{E}}_{\mathrm{ew.}}}.$	0,0038	0,0045	0,0042	0,0024	0,0033	0,0027	0,0027

Analysing data resulted in table 3 and other similar materials, received during experiment, follows, that about 0,3 % of seismoacoustic energy is transformed to hydroacoustic one. At substitution in calculations ρ with higher values the given percentage will proportionally decrease.

Appreciating the loading effects of atmospheric and hydrospheric processes on lithospheric ones we used the data received on coastal laser strainmeters, laser nanobarograph and a laser measuring instrument of hydrosphere pressure variations. The general distinctive features of the given installations from traditional receivers of similar type are reduced to high sensitivity, ability to carry out measurement in a frequency range from 0 up to 1000 Hz in a wide dynamic range. Now in POI FEB RAS works are carried out on development of laser strainmeters of bottom type and laser receivers of power type in which basis of construction vector-phase methods lay. The given installations are created on a basis of Michelson interferometer of equal-arm type in which as a light source the small-sized semi-conductor laser is used.

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