TheVibrational Method for Studying Acoustooptic Interaction at Infralow Frequencies

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***Abstract* – In this paper, the processes of acoustooptic interaction at infralow frequencies are studied usingseismic vibrators as sources of low-frequency acoustic oscillations propagating in the atmosphere and laser measurement lines as optical receivers of oscillations. The source and receiver types being proposed to investigate the acoustooptic interaction determine the novelty and originality of the approach. The results of experiments for estimating the characteristics of the acoustooptic interactionat infralow frequencies are presented.**

***Index Terms* – Acoustooptic interaction, infralow frequencies, seismic vibrator, laser measuring line, optical bench, experimental studies.**

I. INTRODUCTION

THE PROBLEMS of acoustooptic interactionhave a long history. They are mostly associated with studies of light diffraction in the ultrasound and radiofrequency ranges [1-3]. However, acoustooptic interactions in the region of infralow frequencies remain practically unexplored. This is due to the fact that there are no special acoustic radiators in this frequency range. As an alternative to such sources, the authors of the present paper propose using seismic vibrators capable of radiating not only seismic waves in the Earth, but also acoustic oscillations in the atmosphere [4,5]. Among them are the CV-100 and CV-40 centrifugal vibrators [6]. Sincethe radiation of acoustic oscillations is highly synchronous, signals from such sources can be recorded at large distancesby using correlation-spectral accumulation methods. In this case, owing to limited radiation power, the problem of ecological safety when using this type of sources can be solved, in contrast to powerful explosion sources. This opens up possibilities for experimental studies of acoustooptic interactions. The results of such studies are of interest for the creation of combined seismic-acoustooptic information technologies.

The approach being proposed to studying theacoustooptic interaction atinfralow frequencies determines the novelty and originality of the investigations.

II. PROBLEM STATEMENT

Consider the interaction of wave oscillations of various nature, that is, the acoustic wave process

$$\nabla^2 x - \frac{1}{\upsilon^2}\frac{d^2 x}{d t^2} = 0 \tag{1}$$

and the process in themeasurement beam

$$\nabla^2 y - \frac{1}{c^2}\frac{d^2 y}{d t^2} = 0, \tag{2}$$

where υ, c arethe propagation speedsof acoustic and measurement waves, respectively, and ∇^2 is theLaplace operator. Equation (1) admits a solutionin the form of a plane harmonic wavewith an amplitude$A$: $x(t) = A\sin\left(\omega t - \bar{k}\,\bar{r}\right)$, where $\bar{r}$ is the radius-vector, $\bar{k}$ is the wave vector,and $\left|\bar{k}\right| = k = \omega/\upsilon$.

The interaction of the both wave processes is based on the following:an acoustic wave front characterized by acoustic pressure valuesat medium's points causes the emergence of mechanic deformations, a_j, in the medium. Therefore, each acoustic wave is accompanied by a variation of medium's refractive index, n. With allowance for this, for a plane monochromatic acoustic wave propagating along a given direction z the variable refractive index can have the form

$$n(z,t) = n + \Delta n\cos(2\pi f t - kz). \tag{3}$$

Here$n$is an unperturbed refractive index, f and k are the frequency and wave number, respectively, and Δn is theamplitude of variation of the refractive index under the action of the acoustic wave. For incident light, a medium with the refractive index (3) is a diffraction grating moving with a sound speed v. Passing through such a medium, the light is diffracted by inhomogeneities of the refractive index depending on the acoustic wave oscillation frequency.This can result in variations of the amplitude levels and propagation speeds of measurement waves, theirphase-frequencytransformations, which determine the possibilities of "beam reception" of acoustic oscillations.

The conditions of "beam reception" based on the relations between the parameters of the external acoustic field and measurement oscillations are determined as follows:

$$\nu/\omega >> c_0/\upsilon,\ L/rl >> 1,\ \lambda/d > 0.82$$

$$L/\lambda << \begin{cases} c_0^2/c_m\upsilon & at\ c_0/\upsilon >> 1 \\ c_0^2/c_m\upsilon,\ c_0/(\upsilon - c_0) & at\ c_0/\upsilon < 1 \end{cases}$$

Hereν, c_0, $\bar{c}_m$ are the angular frequency, average velocity, and amplitude of the parametric variation of the propagation speed of oscillations in the measurement beam, respectively; L, d are the length and diameter of the measurement beam,

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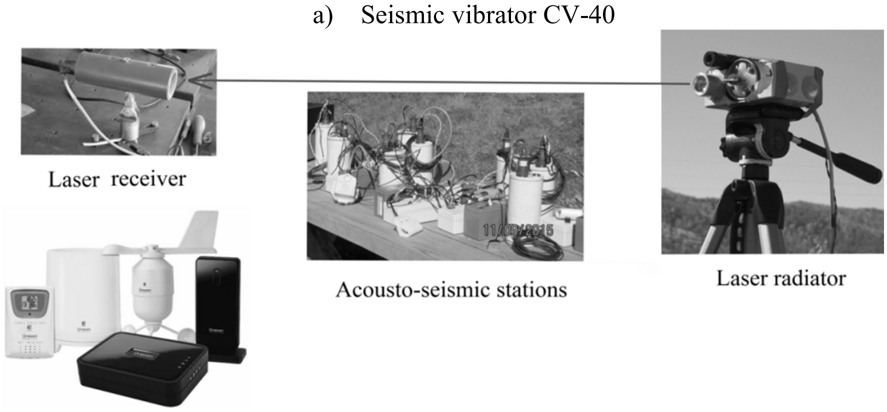
respectively; ω, λ, υ are the angular frequency, wavelength, and propagation speed of external acoustic oscillations; and $r\,l$ is the radius of spatial correlation of medium's inhomogeneities.

The above relations determine the requirements to choosing conditions for recording of acoustic oscillations by a laser measuring line. In real conditions, the recordingis affected by some disturbing factors, such as the atmosphere inhomogeneity, external noise, meteorological factors, etc. All external factors can be taken into account in natural experiments.

III. THE EXPERIMENT AND RESULTS OF DATA PROCESSING

To perform the investigations, a model of anacoustooptic information system has been created by the authors (see Fig. 1).The system consists of the CV-40 seismic vibrator (acoustic radiator), an optical bench including a laser radiator, and an optical receiver. Autonomous digital recording stations located along the measurement beam are used for direct recording of acoustic oscillations. A meteorological station is designed for recording of meteorological parameters in the surrounding atmosphere.

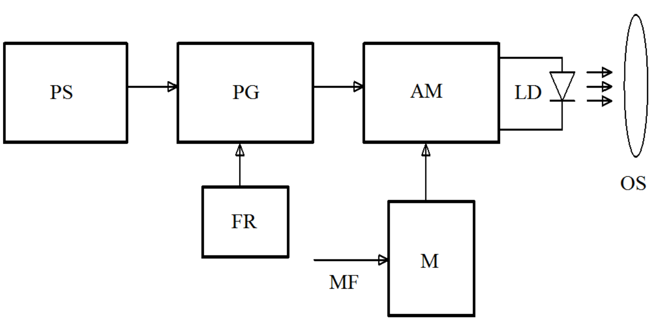
a) Seismic vibrator CV-40



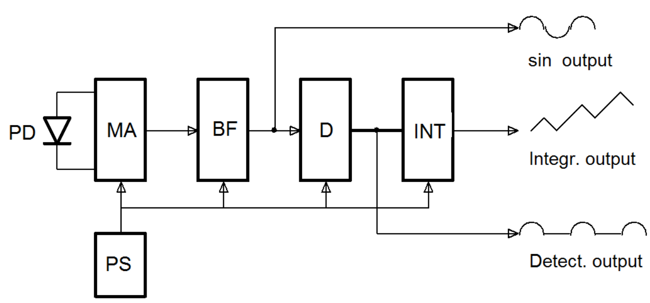
b)

Fig.1.Components of the acoustooptic system: a) seismic vibratorCV-40; b) acousto-optical bench.

A scheme of theoptical bench and its major blocks are shown in Fig.2.Its major modules are:emitter of optical pulses (seeFig.2a)and optical receiver(seeFig.2b). The modulesinclude apower source (PS), a pulse generator (PG), a frequency regulator (FR), an amplifier (AM), a modulator (M), a modulating frequency (MF), asemiconductor laser detector (LD), an optical system (OS), a phase detector (PD), a bandpass filter (BF), a detector (D), andan integrator (INT).



a)



b)

Fig.2. Block diagram of the optical bench.

Fig. 3. Bench with a telescope.

An external view of the bench with a telescope is shown in Fig. 3.

One of the factors characterizing the sensitivity of beam reception is estimation of extremely low level of the amplitude modulation depthof the measurement beam.The idea of measurements in laboratory conditions is based on the principles of amplitude modulation(AM) of laser radiation pumping pulsesup to a given depth from modulatorMby precision harmonic signalsin the frequency range from2 to 20 Hz (Fig.2a),with subsequenttransmission–receiving of pulses along the optical channel.The envelope of the pumping pulses at the optical receiver output (Fig.4) contains information about external actions on the measurement laser beam in the form of amplitude-phase-frequency characteristics.

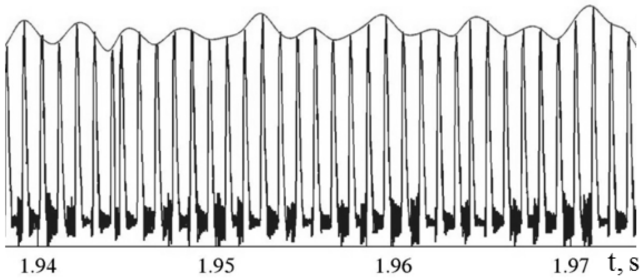


Fig.4. Record of an optical signal with a carrier of 1 kHz amplitude modulated by an acoustic signal and external noise.

They were measured in laboratory conditions on an 80-meter long base (radiator-receiver distance)andin atmospheric conditions usingreflectors. Particular examples of oscillogramsfor the transmission of AM signals and reception ofdemodulated signals are presented in Figs. 5 and 6. Fig. 5 showsoscillograms with a modulation depth of 5.1%in the 80-m long “transmission-reception”base in laboratory conditions.

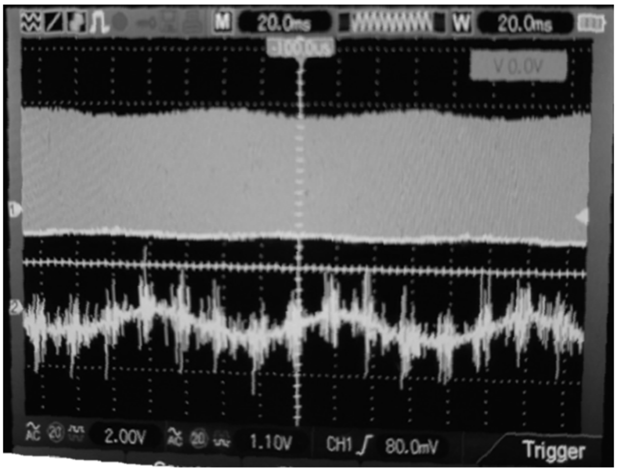


Fig. 5. Oscillograms of an AM signal and a demodulated signal in an 80-m long trace. AM depth: 5.1%

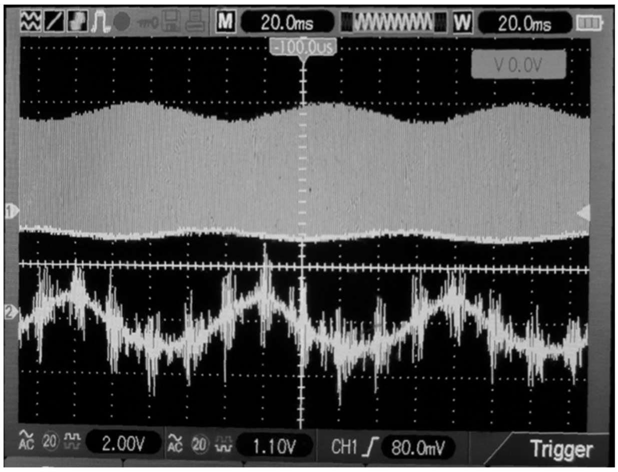


Fig.6. Oscillograms of an AM signal and an output signal in an atmospheric trace. AM depth: 10%

Fig.6 showsoscillograms with a modulation depth of 10% atthe atmospheric base “transmission-reception”. It is evident thatlimiting sensitivity under the action of noise can be reachedby usingdigital methods of processing of the optical signal envelope. Such methods include algorithms for quadrature measurement of the amplitude and phase $\{A,\varphi\}$ of a harmonic oscillation $S(t)$ with a frequency ω_0. For an envelope in the form of an additive signal and noise mixture $Z(t)=S(t)+n(t)$,the parameters calculated forsequential discrete processingare $A[m]=\sqrt{x^2[m]+y^2[m]}$, $\varphi[m]=\mathrm{arctg}\dfrac{y[m]}{x[m]}$, where $x[m]$ and $y[m]$ are quadratures of the form

$$x[m]=x[m-1]+\gamma\left(z_m\sin\omega_0 t_m-x[m-1]\right)$$
$$y[m]=y[m-1]+\gamma\left(z_m\cos\omega_0 t_m-y[m-1]\right). \quad (4)$$

Here $m=1,\ldots N$ is the step number of the recurrence procedure andγ is a parameter determining the convergence rate of the successive estimates $\{A^*,\varphi^*\}$ tosteady-state values. The choice ofγis determined as follows: $\gamma=\Delta t/T$, where*Δt*is the sampling intervalof the initial continuous signal and *T*is the processing interval. An advantage of the algorithm form (1) being usedis that the parameters can be estimated in real time. The algorithm being considered was used for the case of an external modulating oscillation with a frequency of 5 Hzand a modulation depth of 0.4% to obtain the current values of the estimates $\left\{A^*,\varphi^*\right\}$of the demodulated signal (see Figs.7a and 7b, respectively). In the case under considerationT=60s. Quantitative values of steps*m*are shown along the x-axis. Similar results for a modulation depth of 16% and a frequency of 10 Hzare presented inFigs.8a and 8b, respectively.

The final results of estimation of the parameters$\left\{A^*,\varphi^*\right\}$ are determined bytheir steady-state valuesstarting with some iterationm_{st}, whose corresponding values are presented inFigs.7a, 7band8a, 8b. Figs.7candFig.8cpresent, for the cases being considered, the results ofspectral extraction of a modulated signal from an optical signal on the background of noise.

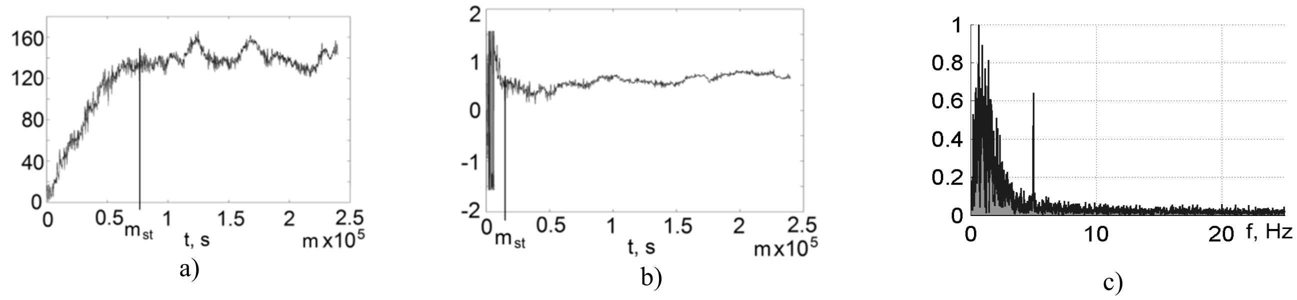


Fig.7. Modulation depth: 0.4%.

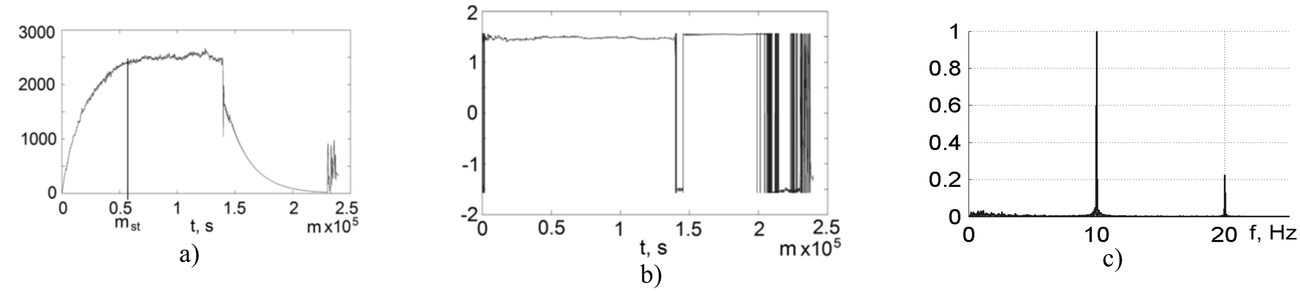


Fig.8. Modulation depth: 16%.

The performed test experiments show that the phase-frequency characteristics allowing one to detect modulation depths of optical signals of up to 0.1% are most sensitive to the acoustooptic interaction. An acoustooptic interactionwith the use of acoustic oscillations of vibrational sourcesis a weakinteraction, which can bedetected only by methods of spectral-correlation accumulation of initial oscillations in noise.Taking into account this, it is important to estimate the upper valuesof distance that can be achieved for the chosen vibrational source typeusing the criterion of detectability of initial acoustic oscillations. This is especially important because the energy levels of acoustic radiation from the vibrator are low.For instance,For instance, the total power of infrasonic radiation into the atmosphere by theCV-40 vibrator is approximately 60 W.

Theoretically calculated trajectories ofinfrasonic waves[7]can cover a linear base on Earth's surface of up to 100 km(Fig.9).Given the above justification, an experiment for the recording of acoustic oscillations from theCV-40 vibrator(Fig.1) along a 100-km long linear profile has been performed. In experiments with the CV-40 vibrator, a method of cross-correlation convolution has been developed and successfully tested. Its signals are, on the one hand, an additivemixture of a weak acoustic sounding signal, which is many times (by an order or several orders of magnitude) smaller than the external noise, and, on the other hand, a reference signal whose shape is the same as that of the sounding signal from the source. As the latter,LFM-signals of the form $s(t) = A\cos(\omega t + \beta t^2/2)$ are used, whereβ is theincrease rate of the source radiation frequencyin the range from 7.91 to 11.23 Hz. Fig. 10 shows the results of mutual correlation convolutions (vibrational acoustograms) versusdistance.

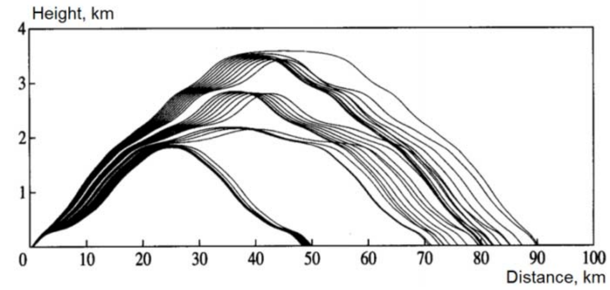


Fig.9. Calculated height profiles of infrasonic waves.

The vibrational acoustograms show that the noise immunity of the results of accumulation is determined, to a large extent, by the external noise level at recording points.For instance, high noise immunity in the process of recording was achieved at a distance of 90 km owing to the choice of a point with a low noise level.

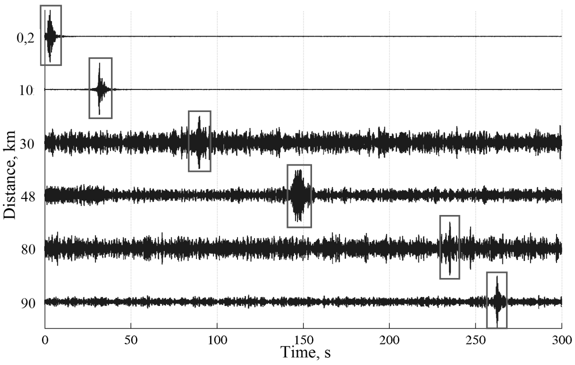


Fig. 10. Results of convolutions of LFM-signals from the CV-40 vibrator versus distance.

Fig. 11showsnormalized plots of attenuation of acoustic and seismic oscillations versus distance.

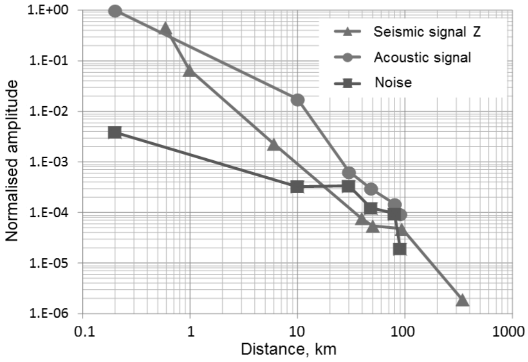


Fig.11. Plots of attenuation of acoustic and seismic waves versus distance.

It follows from the data obtained that the averageweakening of the sound intensitywithin 100 kmis by 4 orders of magnitude, that is, 40 dB. Taking into account the fact that the sound intensity decreases in inverse proportion to the square of the distance from the source(in this case, by a factor of 100^2 (40 dB)), at infralow frequencies the sound attenuation with distance is fully determined by the factor of geometricaldivergence of the acoustic wave front. This means that the factor of absorption of acoustic energy in the atmosphere can be neglected.

IV. CONCLUSIONS.

An approach to studying the process of acoustooptic interaction at infralow frequenciesusing the CV-40 seismic vibrator as a source of low-frequency acoustic oscillations and a laser measurement line has been proposed. An optical bench has been created, and algorithms and programs for the detection of weak acoustooptic interactions at infralow frequencies have been developed. Model experiments for estimation of the sensitivity of the amplitude-phase-frequencycharacteristicsto the acoustooptic interaction have been performed. Natural experimentswith the vibrator to estimate the lawof attenuation ofacoustic radiation from the vibratorat distances of up to 100 km have been carried out.

This work was supported by the Russian Foundation for Basic Research, projects no. 17-07-872-a and 16-07-01052-a.

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