AN ACOUSTOOPTIC INTERRACTION AT INFRALOW FREQUENCIES

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ABSTRACT

An original approach to studying acoustooptic interactions at infralow frequencies using seismic vibrators is proposed. The authors in numerous and natural experiments has been proved that such sources can radiate low-frequency acoustic oscillations, propagating in the atmosphere up to hundreds of kilometers from the source. High-precision metrological properties of vibrators on frequency-time characteristics open up possibility for investigating acoustooptic interactions at infralow frequencies. An acoustooptic system developed by the authors is described. The system consists of the CV-40 vibrator, an optical bench with a laser emitter with a radiation power of up to 6 W at a wavelength of 850-930 nm and a pulse repetition rate of 1 kHz, a set of acoustic measurement stations, and a meteorological station. The results of natural and test experiments on acoustooptic interactions are presented. On sound frequencies as a source of acoustic oscillations were used dynamics with capacity of radiation 20 W. Results of comparative registration of acoustic fluctuations by means of piezoelectric sensors of pressure, and also optical sensors are resulted. In the course of measurements pressure sensors settled down along a measuring laser beam.

Keywords: acoustooptic interactions, infralow frequencies, seismovibrator.

INTRODUCTION

The problems of acoustooptic interactions have a long history. They are mostly associated with studies of light diffraction in the ultrasound and radiofrequency ranges [1, 2]. At the same time, 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. Now there also exist seismic vibrators capable of radiating not only seismic waves in the Earth, but also infralow-frequency acoustic oscillations in the atmosphere. Among them are the CV-100 and CV-40 centrifugal vibrators [3]. Their acoustic oscillations can be recorded at distances of several tens of kilometers. This opens up possibilities for experimental studies of acoustooptic interactions in the frequency ranges under consideration. Today such investigations are highly needed for solving some important applied problems of intruder alarm systems. Hence, the interest of the authors to studying acoustooptic interactions in the infralow frequency range is justified.

I. PROBLEM STATEMENT

The recording of acoustic oscillations in the atmosphere using the laser beam is based on the processes associated with the wave disturbance of laser radiation by an external acoustic field. The disturbed atmosphere at local spatial points causes a change in the parameters of propagation of the laser radiation, in particular, the characteristics of absorption and scattering. This may result in variations of the propagation speed of light waves, their phase-frequency and amplitude characteristics determining the possibilities of the "beam reception" of acoustic oscillations. Acoustic radiators excite in the medium an acoustic wave front characterized by acoustic pressure valuesctive index can be represented as

$$n(z,t) = n + \Delta n \cos(2\pi f t - kz) . \tag{1}$$

Here n is not indignant index of refraction, Δn –amplitude of change n under the action of the acoustic wave defined as $\Delta n = -n^3 pa/2$, where p is the photoelasticity tensor. In the general case the effect of photoelasticity is in changing medium's dielectric permeability ε, under the action of a mechanical deformation, a. For incident light, a medium with the refractive index (1) 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. The diffraction is greatly affected by external factors, such as atmospheric inhomogeneity, temperature, atmospheric pressure, the concentration of particles, etc. This brings up the problem of analyzing the acoustooptic interaction at low frequencies taking into account the influence of external factors.

II. THEORY.

The conditions when optical reception of acoustic oscillations based on the relations between the parameters of the external acoustic field and measured oscillations can take place are determined as follows:

$$v/\omega >> c_0/\upsilon,\ L/rl >> 1,\ \lambda/d > 0.82 \tag{2}$$

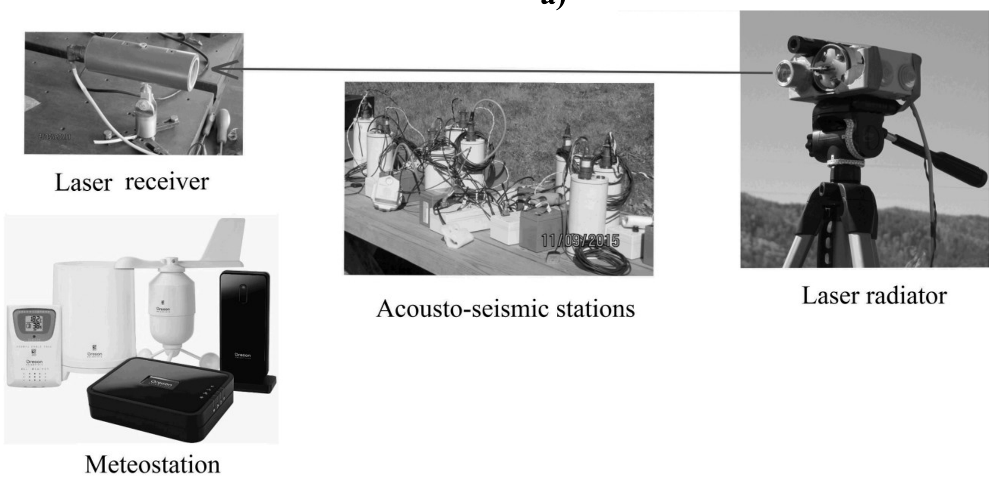
$$L/\lambda << \begin{cases} c_0^2/c_m\upsilon \ \ npu\ c_0/\upsilon >> 1 \\ c_0^2/c_m\upsilon,\ c_0/(\upsilon - c_0)\ \ npu\ c_0/\upsilon < 1 \end{cases} .$$

Here ν, c_0, c_m^{-} are the angular frequency, average velocity, and amplitude of the parametric measurement of the propagation speed of oscillations in the measurement beam, respectively; L, d are the length and diameter of the measurement beam, respectively; ω, λ, v 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. Let the external field be specified as a plane sinusoidal wave: $x(t) = A\sin(\omega t - \bar{\kappa}\,\bar{r})$, where $\bar{r}$ is the radius-vector, $\bar{\kappa}$ is the wave vector, $|\bar{\kappa}| = \kappa = \omega/\upsilon$. When the condition $\lambda >> \lambda_0$ (where λ_0 is the wavelength in the measurement beam) is satisfied, modulation of the measurement wave propagation speed takes place: $c(t) = c_0 \pm c_m \sin(\omega t - \bar{\kappa}\,\bar{r})$. Here c_0 is the propagation speed of oscillations in the measurement beam in the absence of disturbances. The amplitude of wave disturbances is related to the amplitude A_m of variation of the parameter affecting the propagation speed in channel parts of the beam as follows:

$$c_m{}' = \frac{\partial c(t)}{\partial A} \cdot A_m \, .$$

The above relations specify the requirements to optimal conditions of recording of acoustic oscillations using a laser measuring line. Investigations of the above-noted characteristics are affected by the state of the atmosphere characterized by the atmospheric pressure, temperature, concentration of particles, etc. All external factors can be taken into account in experimental studies. To perform such investigations, a model of acoustooptic information system (Fig.1) with the CV-40 seismic vibrator (acoustic radiator), an optical bench including a laser radiator and laser radiation receiver has been created by the authors. A system for multichannel digital recording of seismic and acoustic signals by seismic and acoustic sensors and a scientific meteorological station called "Oregon" (LW301 model) have also been included. The creation of this system is due to the existence of an experimental method in which the acts of radiation and recording of acoustic oscillations, strictly repeated in time, are performed with allowance for the effect of meteorological parameters in the surrounding atmosphere. The structure of the optical bench for signal recording is shown in Fig.2. The generator forms a sequence of control electric pulses of a given frequency, duration, and current. Signals are supplied to the radiator to form optical pulses (Fig.3).

a)



b)

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

In these experiments, an ILPI-107 laser diode with a wavelength of 850–930 nm, a radiation power of up to 6W, a pulse repetition frequency of 1 kHz, and a laser beam intensity divergence angle of 5° is used as a laser emitter. The radiation receiver is based on a KFD-113A2 photodiode. It has a spectral range of 400-1100 nm, a sensitivity in the working range of 0.5 A/W, an effective photosensitive area of the photodiode of 2.75 mm^2, and an amplification coefficient of the operational amplifier of 10 000. The radiation collecting lens has a diameter of 38 mm and a focal length of 28 mm. The signal is recorded by a USB oscilloscope (ASK-3116, Aktakom) with file recording onto the computer. The acoustoseismic system is used to estimate both the acoustic pressure introduced by the acoustic radiators located along the laser measuring line and the velocity of seismic oscillations. To take into account the effect of meteorological parameters on the propagation of acoustic and light waves, the direction and speed of the wind, the temperature and humidity of the ambient air, and the atmospheric pressure are regularly controlled.

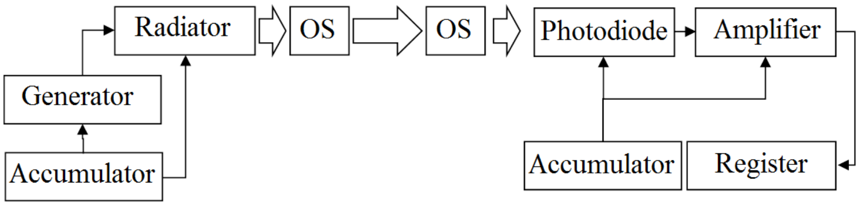


Fig.2. Block diagram of the optical bench.

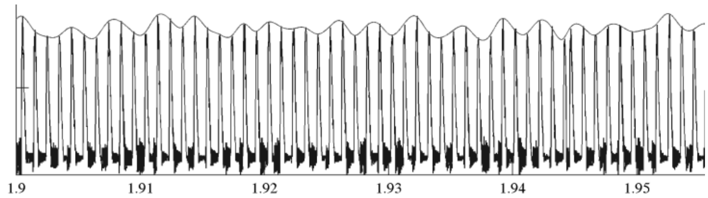


Fig.3. Recording of an optical signal with a carrier frequency of 1 kHz, modulated in amplitude by acoustic signal and external noise

III. RESULTS OF THE EXPERIMENTS.

The acoustooptic system created was used to perform field experiments on the recording, processing, and analysis of the results of acoustooptic interactions. Experiments with the CV-40 vibrator as an emitter of acoustic and seismic oscillations were carried out at the Bystrovka vibroseismic test site (Novosibirsk region). The scheme of location of the acoustooptic system units on a map is presented in Fig.4.

The location of the CV-40 vibrator is shown by an arrow. One can see in the scheme that the “laser source–laser receiver” base is 302 m long. Six autonomous acoustoseismic stations with digital data recording are located along the laser beam with a spacing of 50 m. They make it possible to measure absolute values of acoustic pressure levels in Pa. A preliminary analysis of the characteristics of background optical and atmospheric noise of the laser measuring line in a trace of 302 m at a wavelength of 850…930 nm was performed at the Bystrovka test site. It was found that at a wind in the trace zone of 7 m/s the fluctuations of received signals increase considerably. The histogram of distribution of the amplitudes of received pulses corresponding to the background section is shown in Fig.5. It can be preliminarily concluded that the probability density distribution function is close to a normal one.

Below we present estimates of the levels of acoustic pressure generated by monochromatic acoustic oscillations from the CV-40 vibrator on the acoustic sensors located along the measuring beam (Fig. 4). During the radiation sessions, a sequence of discrete frequency signals of 8.0, 8.5, 9.0, 10.0, and 10.5 Hz lasting 10 minutes each is produced.

Fig.4. Scheme of location of acoustooptic system units and CV-40 vibrator at Bystrovka test site.

The radiated seismic and acoustic oscillations were recorded simultaneously by a three-component seismic sensor, GS-3, along the coordinates X, Y, Z, acoustic sensors, PDS-7, and a laser measuring line composed of the blocks presented in Fig. 2. Optical signals were recorded by a built-in sound card with a sampling rate of 44 kHz. To improve the optical reception of signals the pulse duration was increased to 150 μs. During work at the trace the receiver was defocused to prevent its overloading. The main data processing algorithm is in performing high-resolution spectral analysis of three types of oscillations, namely, seismic, acoustic, and optical ones. Fig. 5 presents particular spectra of such oscillations.The interval of spectral analysis of acoustic oscillations is 3600 seconds and, thus, it covers all radiation sessions of frequency signals. In this case, a frequency resolution of 0.00024 Hz is reached. Fig.5a presents the parameters of the analysis and the spectra of acoustic oscillations, Fig. 5b- the spectra of optical oscillations with the following parameters above the spectra: t-specified time window intervals; a spacing of 0.00298 means that the spectral analysis resolution is in Hz.

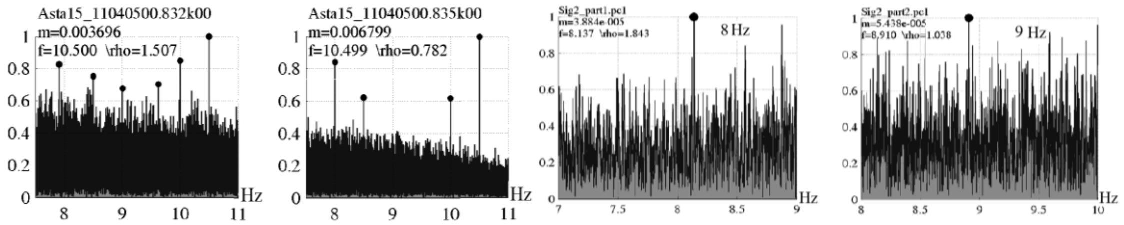
The spectra of optical signals correspond to acoustic radiation frequencies of 8.0, 9.0, Hz. A characteristic feature of the spectra of acoustic and optical oscillations recorded from the CV-40 vibrator is a tendency for the noise immunity factor of reception, characterized by the signal/noise ratio, to decrease. Whereas for acoustic oscillations the obtained spectra have a noise immunity of reception with the signal/noise ratio of about 5, for optical oscillations the noise immunity factor decreases to 2. The decrease in the level of acoustic oscillations is mostly due to the effect of meteorological factors, such as the direction and speed of the wind, the temperature and humidity of the ambient air.

In the case under consideration, the main factor determining the decrease in the level of acoustic oscillations at recording points is the wind direction and speed: according to Fig. 4 the wind is practically directed towards the propagation front of the acoustic wave from the CV-40 vibrator and has a speed of 7 m/s. The acoustic wave level decreases by more than an order of magnitude, which can be seen on the spectra of acoustic oscillations (Fig. 5a).

Estimates of the levels of acoustic pressure introduced by monochromatic oscillations from the CV-40 vibrator along the laser measuring line have been obtained. For the given experimental conditions (the frequencies and duration of monochromatic oscillations, the location of sensors in the profile recording line, see Fig. 4),

acoustic pressure values are within 0.001…0.01 Pa, which corresponds to a noise level of 40…50 dB.

The location of optical signal modes on the frequency axis (Fig.5b) corresponding to the initial acoustic oscillations is affected by the time drift of the optical signal periodicity spectrum in a central frequency zone of 1 kHz. The presence of the drift has been experimentally confirmed by analyzing the spectra. Quantitatively, the drift is about 0.2%, which determines the characteristics of drift of the modes of optical signals.



a)-acoustic sensor b)-laser sensor

Fig.5. Spectra of monochromatic signals and noise of three acoustic sensors and laser measuring line.

The test experiments for comparative analysis of the levels of acoustic and optical signals were based on simultaneous recording and measurement of the levels of acoustic oscillations from two loudspeakers of a power of 20 W each located at a distance of 6–10 m from the line of recording stations. The geometrical characteristics of location of the acoustooptic system units are presented in Fig.6. Acoustic oscillations were radiated at fixed frequencies in a range of 40…140 Hz (40, 60, 72, 80, 90, 100, 140, and 150

Hz). The direction of the acoustic wave front was perpendicular to the light beam. The acoustic pressure levels versus radiation frequencies obtained from the sensors in the light beam propagation line for the given geometry of arrangement (Fig.6) are within 0.01…0.15 Pa.

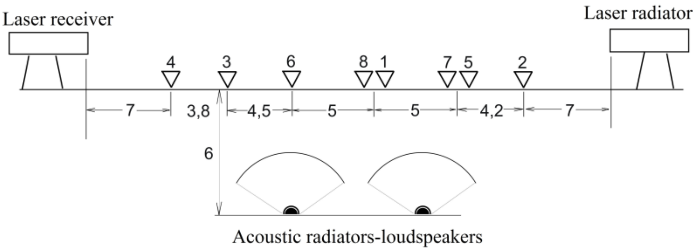


Fig.6. Scheme of location of the acoustooptic system units. Distances are shown in meters.

The modes of acoustic and optical oscillations are identified by high-resolution spectral analysis. As an example of such analysis, Fig.7 (top) presents the spectra of acoustic oscillations recorded by three neighboring acoustic sensors (Fig.6), with a mode at a frequency of 40 Hz.

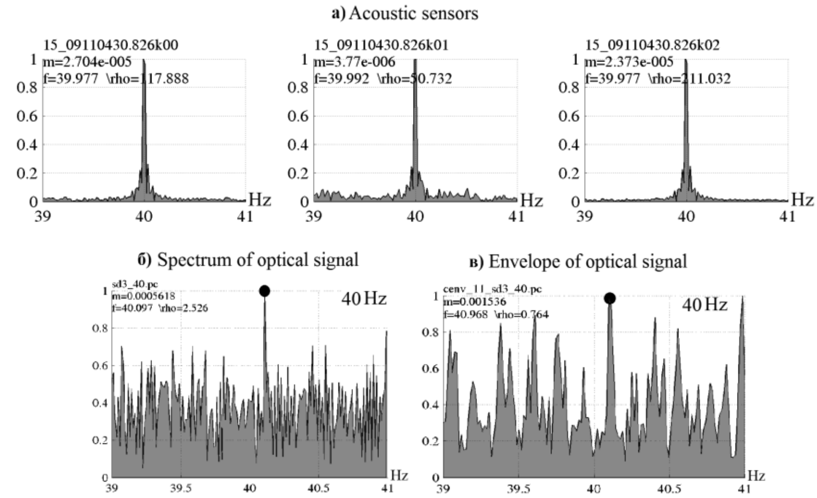


Fig.7. Spectra of monochromatic oscillations with a frequency of 40 Hz recorded by three neighboring acoustic sensors (upper figure) and laser measuring line. Radiation source: loudspeaker of a power of 20 W at a distance of 6–10 m from recorders.

The corresponding signal durations and spectral window values are shown above the spectra. The errors in the deviation of the identified modes in frequency are determined by variations of the optical signal carrier frequency reaching 2%. Fig.8 (bottom) presents the corresponding spectra of optical oscillations obtained in the time intervals that are the same as those of processing of acoustic oscillations. The processing parameters are given above the spectra. It follows from a comparison of the both types of spectra that the noise immunity of optical signals is approximately 5 times less than that of the initial acoustic signals. This difference can be explained by the action of the above-listed external factors (meteorological factors, scattering, absorption in inhomogeneous atmosphere, etc.).

CONCLUSION

– An original acoustooptic system consisting of the CV-40 seismic vibrator, a laser measuring line, and a system of autonomous digital seismoacoustic stations called "Baikal" for acoustooptic investigations in the infralow frequency range has been created. A new feature in the studies of acoustooptic interactions is the use by the authors of a seismic vibrator as a source of acoustic oscillations with high-precision metrological characteristics.

– Experiments on simultaneous recording of acoustic and optical signals from the CV-40 seismic vibrator have been performed. The noise immunity of reception of discrete frequency signals at infralow frequencies and the noise distribution density in receiving signals have been estimated. In the first case, the noise immunity of optical reception is by a factor of 2.5 less than that of direct acoustic reception. The noise distribution density is approximately described by the normal law.

– These works will be developed further using a two-beam laser measuring line and phase methods of detection to increase the noise immunity of reception of acoustic oscillations.

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