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Modeling of the interaction of acoustic and seismic waves from vibrational sources. Statement of the problems*

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The paper deals with the statement of mathematical problems and the analysis of experimental data of physical phenomena, connected with generation, long-distance propagation and interaction of the acoustic and the seismic waves from powerful vibrational sources working on the interface of the elastic Earth - atmosphere. This phenomena were observed for the first time in the experiments with powerful seismic vibrators of the ultrasonic frequency range made in SB RAS, when the acoustic and the induced surface seismic waves were recorded at the distances of 20 and 50 km from the sources.

1. Introduction

The sources operated at the free surface of the ground interact with two media: solid Earth and atmosphere, and generated acoustic and seismic waves. The effect of the intensive acoustic wave excitation by the surface explosion sources is known in seismology and seismic prospecting [1, 2]. An acoustic impulse from explosion propagates along the free surface and induces elastic surface waves. They are recorded on seismograms with the arrival times equal to the travel time of the acoustic wave from the explosion point to the recording point. Experimental data show that the amplitude of elastic surface wave, induced by an acoustic impulse at distances less than one km has more than one order of magnitude larger than the amplitudes of P- and S-seismic waves from explosion [1]. Modeling of the process of acoustic impulse propagation was made in [3].

It was erroneous considered earlier that the radiated acoustic waves from seismic vibrators are extremely small and they can not propagate and been recorded at a large distances. The authors of the present paper experimentally detected the effect of excitation of the acoustic waves and the subsequent induction of surface waves at large distances (20–50 km) from powerful low-frequency vibrational seismic sources [4, 5].

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2. Acoustic and seismic waves from vibrational sources

A powerful seismic vibrators are using in experimental geophysics for the seismic sounding of the Earth and a deep structure research. The following powerful vibroseismic sources were created and used in the experiments in Siberian Branch of RAS: the centrifugal CV-100 vibrator (the force amplitude is 100 tons, the frequency range is 5–9 Hz), the hydroresonant HRV-50 vibrator (the force amplitude is 50 tons, the frequency range is 2–8 Hz), the CV-40 centrifugal vibrator (the force amplitude is 40 tons, the frequency range is 6–12 Hz) [6]. The first series of experiments with recording of monochromatic and sweep-signals and measurement of their parameters was performed with the HRV-50 vibrator. The distance between the radiator and receiver was 20 km. A 15-channel measurement system was used at the recording point. A profile consisting of 5 three-component low-frequency seismic receivers was arranged at a spacing of 100 m.

The series of vibrational correlograms was obtained by convolution of recorded signals with the reference sweep-signal radiated by the vibrator at 3–7 Hz [4]. All correlograms contain a train of oscillations with arrival times of 4–10 s. The first arrivals correspond to refracted P-waves with characteristic velocities of 4–6 km/s, intensive arrivals of SV- and SH-waves and surface waves are observed at a 6–7 s. The impulse response of the medium is 10–15 s. The character of the seismogram is in good agreement with the velocity cross-section of the region. The amplitudes and phases of this train of waves (4–10 s) are kept constant in all experiments.

But a part of correlograms show the second train of oscillations with an arrival time of 57–60 s, which corresponds to velocities of 330–340 m/s at a basis of 20 km. The group wave velocity determined by 5 seismic receivers along the line, also corresponds to this value. Polarization in this train of oscillations is elliptic as for surface waves. A peculiarity of the second train of oscillations (57–60 s) is considerable variation of the amplitude from session to session with a factor of 3–5.

The time and the velocity characteristics of the second train of oscillations made it possible to assume us that it is caused by the arrival of acoustic wave from the vibrator at the recording point. A highly sensitive infrasonic microphone was used in next experiments and recorded acoustic oscillations at the location point of the seismic profile.

The second series of experiments on recording of seismic and acoustic oscillations on the base of 20 km was made using the CV-100 and HRV-50 vibrators and harmonic signals. Radiation sessions of 15 minutes at a constant frequency of 6.4 Hz allowed us to make synchronous accumulation of harmonic oscillations at a recording point with spectral resolution of 0.001 Hz. The spectra of seismic oscillations for three components of seismic

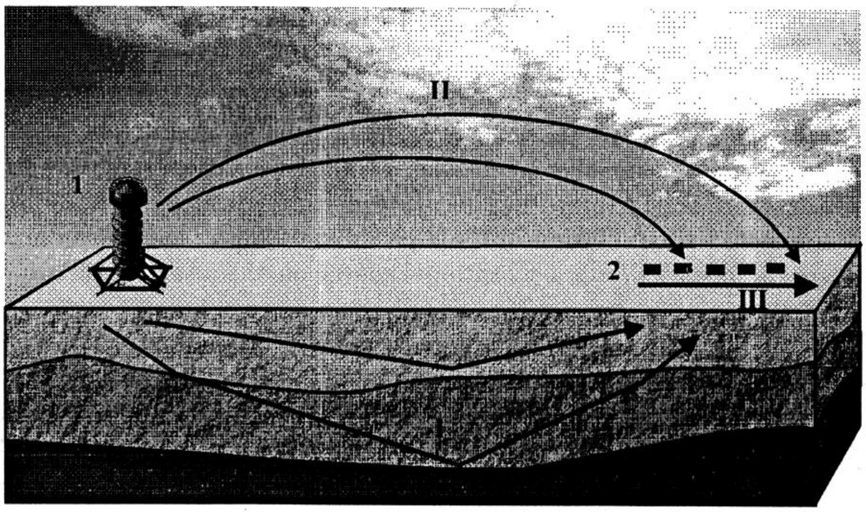

Figure 1. The scheme of the acoustic-seismic effect caused by the action of the seismic vibrator: 1 – seismic vibrator, 2 – seismic array, I – seismic waves, II – acoustic waves, III – surface seismic wave induced by the acoustic wave

receiver and acoustic oscillations recorded by the infrasonic microphone had narrow peaks of the radiation frequency.

Another series of experiments was performed at the offset 50 km to determine the influence of temperature and wind processes in the atmosphere on the effects of interaction of acoustic and seismic fields from vibrational sources. Sessions of radiation with the duration of 45 min were performed at night time using sweep-signals in a frequency range of 6.25–9.57 Hz in order to obtain vibrational correlograms. The meteorological situation along the wave propagation path was fixed by a nearby meteostation [5].

Two trains of waves are present on the correlograms as in the previous case. The first train of waves is observed in all correlograms at 8–14 s. It corresponds to the seismic P- and S-waves. The second train of waves is recorded in the part of correlograms with arrival times of 146–150 s. The propagation velocities of 333–342 m/s of this train of waves which coincide with velocity of the sound in the air correspond to these arrival times.

The experiments have shown that the appearance of the second train of waves is correlated with the wind direction. This train of waves is clearly seen when the direction of the wind coincides with the direction from the source to the receiver. Otherwise, when the direction of the wind is opposite, the second train of waves is not observed. In contrast to seismic waves (which have no fluctuation of arrival times) the fluctuations of the acoustic and the induced seismic wave arrival times are correlated with the wind velocity: the arrival time increases with decreasing of the wind.

3. Mathematical problems of modeling of the acoustic-seismic processes

3.1. Modeling of acoustic waves radiation. The mathematical modeling should make clear the mechanism of acoustic waves radiation by a low-frequency seismic vibrator. The mathematical statement of the problem is connected with solution of the direct dynamic problem for an elastic medium and acoustics with a vibrational source on the interface of two media.

From the physical point of view a mechanism of acoustic waves radiation by the powerful seismic vibrators is as follows. During the work of the vibrators, the ground surface around the source of an area of 500–1000 square meters oscillates as a large membrane of the infrasonic acoustic radiator with an amplitude of 1–5 mm. The surface seismic waves propagating from a vibrator along the Earth's free surface have also a significant amplitude in the vicinity of radiation point and can make contribution to an emitted acoustic energy.

Solution of the dynamic problem will define the full wave field in the elastic Earth and in the atmosphere near the vibrational source. It will allow us to determine a radiation pattern and the emitted acoustic energy in infrasonic range. At present, the combined analytical-numerical methods for this problem in the case of a complicated elastic medium are well developed [7].

3.2. Modeling of long-distance propagation of acoustic waves. The propagation of the acoustic waves of infrasonic frequencies (6–7 Hz) to a distance of several tens of kilometers is possible owing to the phenomenon of refraction of sonic waves in the atmosphere and occurrence of the near-surface wave channel. Two physical mechanisms of this phenomenon are known. They are: the temperature inversion in the air layer near the Earth's surface and the presence of wind with the velocity profile increasing with altitude. In contrast to the seismic channel, the acoustic channel is much more variable and depends on atmospheric conditions. This is responsible for considerable variations the amplitudes of the acoustic and the induced seismic waves, up to their disappearance when the channel vanishes.

The mathematical modeling of long-distance propagation of acoustic waves seems to be a very complicated.

First, the problem is three-dimensional and the model of a medium should include characteristics of a real atmosphere – the altitude distribution of a density, temperature and velocity of a wind. It will allow the investigation of conditions of the formation of the near-surface wave channel.

Second, the size of an area of modeling should exceed 1000 waves lengths (for the frequency 6 Hz, the length of an acoustic wave being 50 m). For the

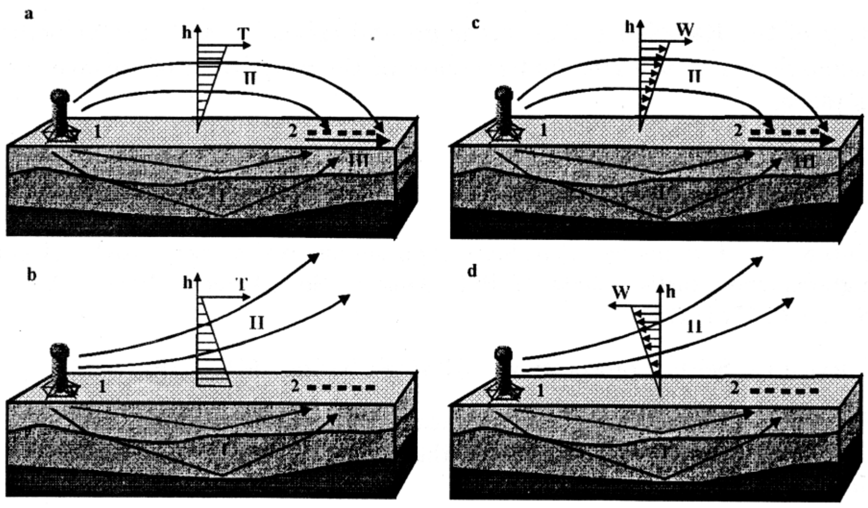

Figure 2. The propagation of the acoustic waves from vibrator: a) and b) in the presence of temperature profile near the surface, c) and d) in the presence of wind profile; 1 – seismic vibrator, 2 – seismic array, I – seismic waves, II – acoustic waves, III – induced seismic wave, T – temperature, W – wind, h – altitude

modern numerical methods the solution of the 3-D direct dynamic acoustic problems needs the calculations available only for the supercomputers.

And third, it is necessary to take into account the statistical regularities of variations of parameters of the atmosphere during the sessions of radiation (about 1 hour). Apparently, at the present time, the study of the near-surface wave channel and the long-distance propagation of acoustic waves is possible only on sufficient simple models for clearing up the qualitative characteristic of the process.

3.3. Modeling of acoustic-seismic induction process. The mathematical problems of the interaction of the acoustic wave with the elastic Earth and the induction of the surface seismic wave in the point of the recording of the seismic signal are close to the fist problem. The mathematical statement is the solution of the direct dynamic problem for an elastic medium and acoustics without the source but with the acoustic wave moving along the interface of two media.

For the simple model with homogeneous acoustic and elastic half-space the mechanism of the surface seismic wave excitation caused by the acoustic wave arrival at the recording point (acoustic-seismic induction) was validated in mathematical simulation of the process [8]. It was shown that when the atmospheric acoustic wave propagates along the boundary of the elastic half-space, a surface wave is induced. This surface seismic wave propagates with the velocity equal to the sound velocity in the atmosphere. If the velocity of the Rayleigh waves in the ground coincides with the velocity of the acoustic wave, the resonant increase of the amplitude of surface waves takes place.

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