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A STUDY OF HIGH-FREQUENCY SEISMIC WAVES BY MEANS OF A GAS-JET SOURCE

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The problem of detection and diagnostics of various soil inhomogeneities with reference scale $l \gtrsim 1$ m is important for seismic tomography and other fields of applied mechanics. To solve a number of relevant issues, a source is needed, which is capable of generating seismic waves with an adequate amplitude at required distances with frequencies $f \lesssim 1$ kHz. Since seismic waves decay as the frequency increases [1], it is necessary to consider the key question of spatial propagation of seismic waves with frequencies $f \lesssim 1$ kHz.

There are various methods of generating artificial seismic fields necessary for sounding the Earth's inhomogeneities [2]. It is known that explosive methods have significant shortcomings because of the destructive effect of explosion on the soil [3, 4]. Various alternative methods of generating seismic fields by means of sources of periodic long-term impact upon the soil have been suggested and tested by Makaryuk et al. [2].

Although there are various vibrators, the problem of creating a simple and economic source that meets some specific requirements is still pressing.

A continuous-periodic source of seismic waves based on a gas-jet auto-oscillatory system was developed and tested at the Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences by Yanenko et al. [5]. A Helmholtz resonator (hollow rectangular parallelepiped with a cylindrical neck) is aligned coaxially to the nozzle. An air jet enters the resonator, and pressure fluctuations arise in the resonator cavity under known conditions. Their frequency is determined by the cavity and neck dimensions, and their amplitude is determined by the stagnation pressure and the system dimensions. If this cavity is placed in soil, its walls being made of an elastic material, the pressure fluctuations in the cavity will affect the adjacent soil particles and initiate a seismic disturbance in the form of a wave process.

A source that operated on this principle was previously created and tested for a 2–10-Hz frequency range, which corresponds to seismic wavelengths $\lambda \gtrsim 100$ m. Since the spatial resolution of the method of seismic tomography for studying soil objects increases with radiation frequency, it is necessary to have, in some practical areas (geology, civil engineering, archeology, etc.), a source operating in the frequency range 100–1000 Hz, which roughly corresponds to wavelengths of 10–1 m.

The available traditional impulse and electrodynamic stationary seismic sources for this frequency range are used in seismic surveys at high frequencies and for geoacoustic sonic tests [1]. In the source scheme described in [5], an increase in the seismic wave frequency leads to a decrease in the surface area from which a seismic wave is emitted, i.e., to a smaller seismic power.

At high frequencies of the seismic field, a strong decay of seismic disturbances with frequency growth is observed. For reliable signal registration at specified distances, an adequate power of a radiation source is needed as well.

In the present paper, we describe a source based on a gas-jet auto-oscillatory system for the frequency range $f \simeq 100$–1000 Hz. In addition, we give the results of investigation of its seismic field and of the experiments on detection of seismic wave decay at various frequencies within this range, depending on the

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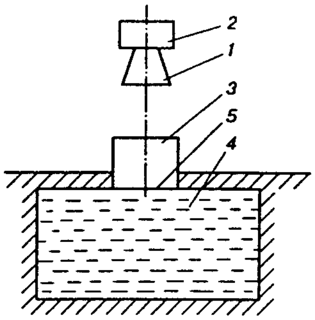

Fig. 1

distance from the source and on detection of a previously created inhomogeneity (buried object) in the soil on the basis of the seismic signal registered.

1. Let us consider the operation principle of the source and its design. The gas-jet source is based on the known gas-dynamic effect. A jet with jet pressure ratio n is exhausted from the nozzle with the exit Mach number $\mathrm{M} \geqslant 1$. If a certain semi-closed cavity, for example, a rectangular parallelepiped with a neck, is mounted coaxially to the jet at a distance approximately equal to the length of the first "barrel," an auto-oscillatory flow regime occurs. The oscillation frequency coincides, to a good accuracy, with the eigenfrequency of the system as a Helmholtz resonator:

$$f = (c^*/2\pi)\sqrt{S^0/l^0W}. \tag{1.1}$$

Here S^0 is the cross-sectional area of the neck, l^0 is its length, W is the cavity volume, and c^* is the sound velocity in the gas.

The amplitudes and phases of oscillations are approximately equal at all points of the cavity. The amplitude of pressure fluctuations in the resonator cavity δp depends on the gas-dynamic parameters of the jet (M, n) and on the geometry of the cavity.

The resonator placed in the soil generates seismic waves. The frequency of these waves is found from (1.1), while the power radiated into the soil has the form [6] $N = (1/2)F\dot{u}\cos\varphi$, $F = \delta pS$ (F is the amplitude of the force applied to the soil), S is the total area of the elastic resonator walls, $\dot{u}$ is the amplitude of the displacement velocity of the soil particles immediately adjacent to the resonator walls, and φ is the phase difference between the force and displacement-velocity fluctuations.

The source design should be capable of generating seismic waves in a necessary frequency range (the radiation frequency should be easily tunable) and should have an adequate radiation power for reliable signal registration at distances to the radiation source prescribed by the conditions of a specific problem. It should also be easy to fabricate, reliable, and not expensive.

Following from the required values of $\lambda \simeq 10$–1 m and the phase wave velocity in sandy-clay soils $c \simeq 1000$ m/sec, we obtain the frequency range of the source $f \simeq 100$–1000 Hz. In accordance with (1.1), we then find the characteristic size of the resonator cavity to be about 0.1 m, at which the attainable power of the source seems to be insufficient.

To preserve the area of the radiating surface of the source in the frequency range $f \simeq 100$–1000 Hz, a new source design was developed. Its sketch is shown in Fig. 1. The source consists of a supersonic nozzle 1 with a stagnation chamber 2 which are mounted coaxially to a variable-length resonator 3. The resonator is separated from a chamber 4 by a membrane 5. A constant-volume fluid-filled chamber is placed in the soil. The walls of this chamber are made of elastic material (rubber). The resonator dimensions are specified and determined by the necessary frequency of auto-oscillations [7]. The gas-pressure fluctuations in the resonator are transmitted through the membrane to the liquid-filled chamber, where oscillating forces affecting the elastic chamber walls and the soil arise.

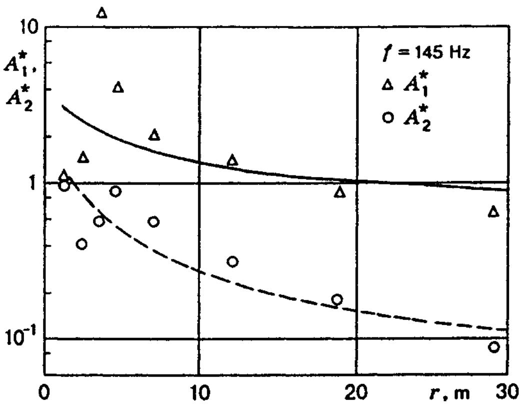

Fig. 2

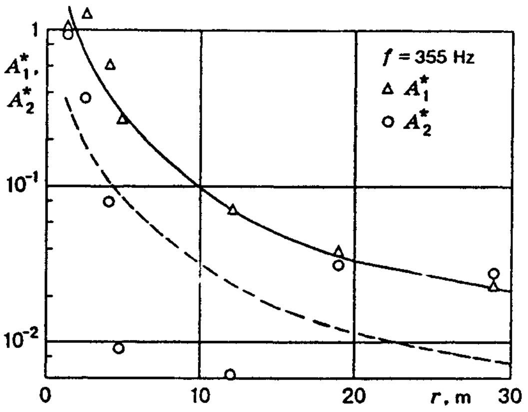

Fig. 3

As we shall show below, this design of a gas-jet source allows one to generate seismic disturbances with small wavelengths, to operate at a high frequency ($f \simeq 1$ kHz), and to obtain seismic waves of adequate power.

In designing this source, a number of fundamental problems for effective operation of the source and some engineering problems for its fabrication and trial operation were taken into consideration. The fabricated model of the source has three replaceable resonance tubes of different lengths, each with diameter 0.04 m. The mounting of an LKh-610 pressure gauge was envisaged in a 300-Hz resonator. An external water-filled chamber was shaped like a cube with a face length of 0.33 m. The horizontal walls were made of metal, and the vertical walls were made of rubber 0.008 m thick. The area of one rubber wall was 0.0784 m^2. Another LKh-610 pressure gauge was placed in the upper wall of the chamber. The exit diameter of the conical nozzle was $d = 0.03$ m.

2. A system of measurements of the characteristics of seismic fields induced by the source was determined by the problems and by the program of tests of the gas-jet source. The experiments were aimed at evaluating the serviceability of the model as a generator of seismic waves, the decay of seismic waves with distance from the source for various frequencies, and the response of seismic waves to local inhomogeneities in the soil.

The pressure fluctuations in the fluid-filled chamber and the characteristics of the seismic field from the source were measured by LKh-610 pressure gauges and also by SG-10 seismic gauges for horizontal displacement velocities and SV-5 gauges for vertical displacement velocities. The signal from a pressure gauge was applied to an amplifier, then to an S5-3 harmonic analyzer and, finally, to an S1-69 oscilloscope. The signals from the seismic gauges arrived immediately at the S5-3 harmonic analyzer and the oscilloscope. Both seismic gauges were placed in the soil almost at the same point, and after one measurement, they were moved to the next point along a chosen "daytime surface" ray emanating by the source of seismic disturbances. Thus, all seismic-field characteristics were measured by one pair of SG-10 and SV-5 gauges. The pressure in the stagnation chamber was measured by a standard pressure gauge and amounted to $3 \cdot 10^5$ Pa in all experiments. The nozzle and entrance of the resonator were 0.038 m apart.

The following experimental procedure was used. A resonator of proper length (0.036, 0.182, and 0.6 m) was connected to the fluid-filled chamber located in the soil, and the nozzle and the resonator were positioned at a distance equal to the length of the first "barrel." A pair of SG-10 and SV-5 seismic gauges was placed at a chosen distance from the source, the system was triggered, and the indications of the pressure gauges in the fluid-filled chamber and those of the seismic gauges were read. After that the gauges were moved to the next point of measurements. This procedure was repeated for all chosen oscillation frequencies.

For all frequencies used, the amplitudes at a certain radiation frequency were measured when the source was idle, which allowed us to evaluate the level of seismic background at this frequency. To prevent the effect of the acoustic field on the indications of the seismic gauges, special measures were taken for acoustic

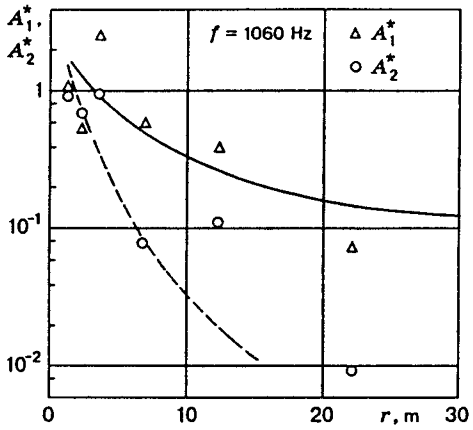

Fig. 4

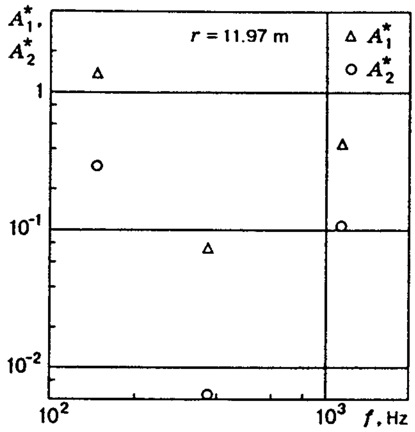

Fig. 5

TABLE 1

r, m	$f = 145$ Hz		$f = 355$ Hz		$f = 1060$ Hz	
	A_1^0/A_1	A_2^0/A_2	A_1^0/A_1	A_2^0/A_2	A_1^0/A_1	A_2^0/A_2
1.25	$5.1 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$	$5 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$
2.43	$1.8 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$	$5 \cdot 10^{-3}$	10^{-1}	$1.8 \cdot 10^{-2}$
3.43	$3.4 \cdot 10^{-4}$	$2.2 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	$3.1 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$
4.68	$6.7 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$9.1 \cdot 10^{-3}$	$2 \cdot 10^{-1}$	—	—
7.00	$1.4 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$	—	—	10^{-1}	$1.2 \cdot 10^{-1}$
11.97	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	10^{-1}	$3.3 \cdot 10^{-1}$	$1.2 \cdot 10^{-1}$	$1.1 \cdot 10^{-1}$
18.67	$3.3 \cdot 10^{-3}$	$7.4 \cdot 10^{-3}$	$1.9 \cdot 10^{-1}$	$8.3 \cdot 10^{-2}$	—	—
22.02	—	—	—	—	$< 6 \cdot 10^{-1}$	$< 6 \cdot 10^{-1}$
28.56	$4.4 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	$4.5 \cdot 10^{-1}$	$7.7 \cdot 10^{-2}$	—	—

separation of the gas-jet source and the seismic gauges.

The above procedure was used to measure the characteristics of seismic fields generated by the gas-jet source at different frequencies. The results are shown in Figs. 2–4, where the following notation is used: $A_1^* = A_1(r)/A_1$ ($r = 1.25$ m) and $A_2^* = A_2(r)/A_2$ ($r = 1.25$ m). Here A_1 and A_2 are the signal amplitudes of the seismic gauges of vertical and horizontal displacement velocities, respectively, r is the distance between the resonator and the measurement point, and f is the signal frequency. It is seen from Figs. 2–4 that each component of seismic disturbances behaves nonmonotonically, depending on the distance to the source. In our opinion, the emergence of signal maxima is due to the influence of soil inhomogeneities and, in particular, to the contribution of reflected waves.

For the measurement points in the soil, the values of the ratio of the background seismic signals with an idle source to the signals of seismic disturbances with the source switched on are listed in Table 1 (A_1^0 and A_2^0 are the amplitudes of signals of the seismic gauges with an idle source). Clearly, the amplitudes of disturbances from the source are much higher than the level of seismic background for the corresponding frequencies at most measurement points.

To estimate the amplitudes of vertical and horizontal displacement velocities, Table 2 lists the amplitudes of displacement velocities at the first measurement point ($r = 1.25$ m). The seismic-field amplitudes are plotted in Fig. 5 as a function of the frequency at a fixed measurement point. An increase in the signal amplitude in the 360–1060-Hz range is probably caused by the stronger effect of soil inhomogeneities with decreasing radiation wavelength in this frequency range.

Using the least-squares technique, one can obtain exponential empirical formulas $A^* = A_0(r^*)^{-m}$ for nondimensional amplitudes of seismic waves A^* versus the distance r^* to the source. Here r^* is

TABLE 2

f, Hz	A_1, m/sec	A_2, m/sec
145	$26 \cdot 10^{-6}$	$17 \cdot 10^{-5}$
355	$15 \cdot 10^{-6}$	$53 \cdot 10^{-6}$
1060	$7 \cdot 10^{-6}$	$9 \cdot 10^{-6}$

TABLE 3

f, Hz	A^*	A_0	m	α, m^{-1}	Q	c^1, m/sec
145	A_1^*	3.04	0.37	0.051	12.8	750
	A_2^*	1.08	0.68	0.085	2.44	2960
355	A_1^*	1.71	1.39	0.122	13.0	760
	A_2^*	0.34	1.23	0.427	1.19	4050
1060	A_1^*	1.65	0.82	0.176	27.0	740
	A_2^*	2.74	2.19	0.492	3.07	3250

nondimensionalized relative to the coordinate of the first measurement point ($r = 1.25$ m). The values of the exponents m and A_0 for various frequencies are listed in Table 3. These empirical curves are shown in Figs. 2–4 by solid and dashed curves for the displacement-velocity amplitudes A_1^* and A_2^*, respectively.

It should be noted that the above empirical formula describes the behavior of the amplitudes in the mean. It does not reflect the nonmonotonic character of the dependence of A^* on r^*, which is apparently caused by the contribution of secondary waves. At present, the authors are not aware of theoretical models that make possible a comparison with the experimental data presented here.

Estimation of the wavelengths for the measured frequencies show that the fronts of seismic waves can be considered plane to a reasonable accuracy in most r-based measurements, except for the neighborhood of the source. This allows one to ignore the divergence of the wavefront. One can also assume that the soil conditions on the experimental area are such that there are no distinct boundaries in the source–detector direction, which would lead to wave reflection and refraction. The decrease in signal amplitudes is mainly attributed to absorption because of irreversible heat losses and diffusion scattering on small inhomogeneities [1].

It is known [1, p. 37] that the absorption-induced decay is introduced as the exponential factor

$$A^*(f) = \exp\left[-\alpha(f)r\right], \tag{2.1}$$

where α is the frequency-dependent absorption factor. This model is not strictly justified theoretically [1], but is quite suitable for an approximate description of the absorption phenomenon observed in reality.

To use the decay model (2.1), it is necessary to exclude the signal-amplification regions from the experimental data in Figs. 2–4 and leave only the points describing the decay of wave amplitudes. Having represented experimental results by an empirical formula of the form $A = A_0 \exp(-\alpha r)$ for all the frequencies f examined, one can determine the absorption factor α related to the quality factor Q by the following relation [1]:

$$Q = \pi f/(c\alpha). \tag{2.2}$$

The results of this procedure are shown in Table 3 for the vertical and horizontal wave components. It is seen that the absorption factors increase with frequency for both wave components, which is in agreement with the general concept.

The available data on the absorption factors of longitudinal waves for various frequencies in sedimentary rock [1, p. 38] are in reasonable agreement with the results of Table 3.

Using the phase wave velocities obtained previously at the Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences on the same experimental site with the frequency $f \simeq 10$ Hz ($c_1^0 \simeq 760$ m/sec and $c_2^0 \simeq 2200$ m/sec, where c_1^0 and c_2^0 are the vertical and horizontal wave velocities, respectively), one can estimate, from (2.2), the mean quality factor of soil for the vertical and horizontal directions. The results are presented in Table 3 for Q. It is usually assumed that the velocity c and the quality factor Q in formula (2.2) are not dependent on each other for all components. This assumption is valid if the frequencies do not change within wide ranges, and the values of Q are rather large. The phase

TABLE 4

Point number (Fig. 6)	A_1	A_2	A_1^0	A_2^0
	mV			
1	10^{-2}	$5 \cdot 10^{-3}$	10^{-3}	10^{-3}
2	$4 \cdot 10^{-2}$	$33 \cdot 10^{-3}$	10^{-3}	10^{-3}
3	$16 \cdot 10^{-3}$	$16 \cdot 10^{-3}$	10^{-3}	10^{-3}

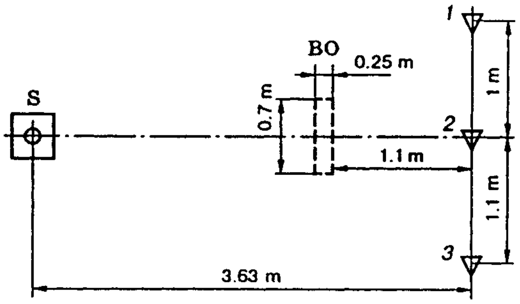

Fig. 6

velocities c, the frequency f, and the quality factor Q are related by the relation [1]

$$c(f_1)/c(f_2) = 1 + (1/\pi Q)\ln(f_1/f_2). \tag{2.3}$$

This approximation for dispersion is quite suitable when the value of Q remains virtually constant in the seismic range of frequencies [8].

Using (2.3) and the data of Table 3 for Q, one can estimate the phase velocities c^1 for the frequency range 100–1000 Hz. The results of this estimation for velocities of both components are presented in Table 3.

Note that the longitudinal-velocity component changes more substantially ($\simeq$84%) with radiation frequency than the vertical-velocity component.

The possibility of registering specially created soil inhomogeneities (buried objects) by varying the seismic-field amplitude was experimentally studied. One experiment is shown schematically in Fig. 6 (top view). Here S is the seismic-field source, BO is the buried object (rectangular parallelepiped), and 1–3 are the points at which the detectors of seismic signals were installed. A 0.025 x 0.7 x 1.2-m parallelepiped was flush mounted with the soil surface. Two largest (0.7 x 1.2 m) faces of the parallelepiped are made of rubber. The distances between the source, the buried object, and the detectors are indicated in Fig. 6.

The signal frequency was $f = 1040$ Hz. The changes in the seismic-field characteristics were measured again by one pair of SV-5 and SG-10 gauges. The experimental results are presented in Table 4. A considerable change in the seismic-field amplitude was noted at central point 2 behind the object.

Since the products of the transverse and longitudinal components of the wave vector by the characteristic transverse size of the parallelepiped are equal to $0.7k_1 \simeq 6$ and $0.7k_2 \simeq 1.5$, respectively, complex diffraction-interference phenomena occur behind the buried object (similar phenomena in gas media were described, for example, in [9, p.220]). In particular, the interference peaks of oscillation amplitudes can be formed at the centerline behind the object.

Possibly, the increase in the signal amplitude at point 2 is caused by the imposition of an additional disturbance reflected from the parallelepiped wall. Note that the distance from the buried object to point 2 is approximately multiple to the half-lengths of the seismic-field waves from the source; therefore, the signal reflected from the wall leads to an increase in the signal amplitudes at point 2.

At lateral points 1 and 3 outside the obstacle influence region, signals that approximately correspond to the free seismic field from the source were observed. A certain difference in the seismic-field amplitudes at points 1 and 3 is explained by the asymmetric position of these points with respect to the axis of the buried parallelepiped.

Thus, the gas-jet source described in the paper can effectively generate a seismic field in the frequency range 100–1000 Hz. The specific features of the behavior of seismic-field amplitudes depending on the distance from the source and on the frequency have been revealed. The absorption factors and the phase velocities at high frequencies have been obtained. The method of seismic sounding can be effective for detection of small-scale objects in the soil.

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