Nonlinear dynamics of seismic vibrators

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***Abstract*–Monitoring of the natural and technogenic environment is one of the most important priority directions in the development of science and technologies. A major problem here is the prediction and prevention of ecological risks for the environment caused by the action of destructive natural and technogenic events and processes. For this purpose a fundamentally new, ecologically clean, and high-resolution method is active vibrational monitoring. It involves tracking of the temporal dynamics of boundary lithosphere-atmosphere" media in response to the action of metrologically precise sounding oscillations of seismic vibrators. The process of excitation of wave fields by such vibrators is accompanied by complex physical phenomena in the source zone, which continue at considerable distances from it. These include nonlinear processes of interaction between the source and the medium and those of radiation of conjugate wave oscillations (seismic, acoustic, electric, and electromagnetic ones). Analysis of these phenomena and estimation of their quantitative characteristics are of purely scientific and practical value. In this paper, original results of experiments aimed at solving the above problems are presented.**

***Keywords*–active geophysical monitoring, seismic vibrators, nonlinear dynamics, conjugate wave fields, experimental data.**

I. Introduction

The problem of active monitoring of the natural environment for the purpose of prediction and prevention of ecological risks from natural and technogenic disasters is a priority direction in the development of science and technologies. Since the 1980s, some powerful seismic vibrators with a disturbing force amplitude of 40…200 tons in the frequency range of 1…15 Hz and low-power seismic-prospecting vibrators with a disturbing force amplitude of 10…20 tons in the frequency range of 10…100 Hz have been developed and manufactured as instruments for solving the problem of active geophysical monitoring [1, 2]. The process of radiation of seismic wave fields by such vibrators is accompanied by a nonlinear physical phenomena in the source zone, which continue at considerable distances from it [3–6] . The results of works on nonlinear dynamics of seismic vibrators are in agreement with the solutions to fundamental problems in studies of the nonlinear dynamics of the geological medium [3, 4]. This is determined by the fact that vibrators are instruments with good metrological characteristics, which make it possible to measure with high resolution the characteristics of nonlinearity of geodynamic processes. In this case identification of nonlinearity effects of the sources is important. In addition to a seismo-physical field, the "vibrator–ground" system generates acoustic and electromagnetic fields [7–9]. For such fields nonlinear effects of radiation also are characteristic. This shows the significance of investigations on the subject of the present paper.

II. Problem Statement

Some important factors in the interaction of vibrators with the medium are nonlinear character. They are determined by the following: disconnectedness of the source and the underlying surface, change in its rigidity parameters during sounding sessions, out-of-phase interaction of individual vibrator platform parts with the ground surface and, finally, the construction of the source itself. Since vibrators are being used more and more in the world, study of such phenomena is timely.

Oscillations of a seismic vibrator in the monochromatic radiation mode are described by the equation

$$m\ddot{u} + R_n\dot{u} + k(u)u = F\sin\omega t + P_0 . \qquad (1)$$

Here m is the vibrator mass, F is the exciting force of action of the vibrator on the ground, $P_0 = mg$ is the vibrator weight, $k(u)$ is the medium's rigidity, R_w is the active resistance of radiation, and u is the vibrator platform displacement. In the case that $F>P$, the vibrator radiating platform separates from the ground. At the time of separation the vibrator displacement $u=0$. At $u<0$ the source is in "free flight". The connectedness of the source with the medium is determined by the condition $u \geq 0$. Usually the vibrator separates from the medium in the zone of resonance of the "vibrator–ground" system, which causes the emergence of harmonics in radiated seismic oscillations. This brought up an idea of "anchoring" the source to the underlying medium, providing its motion together with the oscillating platform and increasing "added" mass of the source. Finally, this increases the exciting force F.

In the case of hydraulic vibrators [1], the effect of radiation nonlinearity is due to nonlinear properties of the air spring supporting the oscillating mass. Here nonlinearity manifests itself in the fact that the air spring works as an elastic element only in compression, which determines the asymmetry of the half-waves of radiated oscillations as the liquid column moves down and up.

In the case of the nonlinear radiation mode, the total radiation power is redistributed between the main radiation frequency and harmonics:

$$N_{\Sigma} = \frac{1}{2}\left(|F_0||v_0|\cos\varphi_0 + \sum_{i=1}^{N}|F_i||v_i|\cos\varphi_i \right)$$

Here F_0, v_0 ,and φ_0 are the exciting force, the ground displacement speed, and the angle of phase shift between them on the main harmonic, respectively; F_i , v_i , and φ_i are the force, speed, and the angle of phase shift at the i-th harmonic.

The authors of the present paper have accumulated considerable experimental material on the nonlinear dynamics of sources of various classes with a disturbing force amplitude of 10…100 tons and in the frequency range of 5…100 Hz. Some results are presented here.

III. Results of the Experiments

To study the nonlinearity factors of radiation of oscillations by seismic vibrators, we performed some experiments on signal recording directly in the zone of four sources. These include: the centrifugal vibrator CV-100 (a disturbing force amplitude of up to 100 tons in the frequency range of 5…12 Hz), the centrifugal vibrator CV-40 (a disturbing force amplitude of up to 40 tons in the frequency range of 6…15 Hz), the hydroresonant vibrator HRV-50 (a disturbing force amplitude of up to 50 tons in the frequency range of 1…15 Hz), and the mobile vibrator CV-10/100 (a disturbing force amplitude of up to 10 tons in the frequency range of up to 10…100 Hz). The type of oscillations radiated into the medium is described by a harmonic function with increasing frequency (sweep signal):

$$S(t_i) = A(t_i)\cos\left(2\pi f_0 t_i + \beta t_i^2/2\right), \quad (i = 1,..N), \qquad (2)$$

where $A(t_i)$ is the signal envelope, f_0 is the initial frequency of the sweep signal, $\beta = const$ is a coefficient determining the frequency sweep rate in time, and $N=T/\Delta t$ is the number of discrete samples of a signal with a sweep duration T and sampling time interval Δt. For certain types of vibrators T is given taking into account Earth's sounding depth.

The nonlinearity effects of radiation of seismic oscillations were estimated using spectral-time functions based on the calculation of the Fourier transform with respect to sweep signals of the form (2):

$$F(k,l) = \sum_{n_1=0}^{N}\sum_{l}^{L} S_l(t_n)\exp(-i2\pi n_1 k/N), \qquad (3)$$

where $n_1=1\ldots N$; $l=1\ldots L$.

The spectral-time functions (STFs) calculated using records of oscillations of the form (2) for four vibrators are presented in Fig. 1. These are the centrifugal vibrators CV-100 and CV-40, the hydroresonant vibrator HRV-50, and the seismic-prospecting vibrator CV-10/100. Oscillations were recorded directly in the zone of radiation of the sources. Fig. 1a shows STFs of a CV-100 signal with a duration of 600 s in the frequency range of 6.25…9.5 Hz, Fig. 1b – of a HRV-50 signal with a duration of 1400 s in the range of 5…7 Hz, Fig.1c – of a CV-40 signal with a duration of 2400 s in the range of 6.25…9.57 Hz, Fig. 1d – of a CV-10/100 signal with a duration of 60 s in the range of 10…60 Hz. In all the cases the STFs correspond to records along the vertical component, Z. It follows from analysis of the STFs presented that the effects of nonlinearity of radiation from different vibrator types differ considerably. They are least pronounced for the powerful vibrator CV-100, for which the level of the second harmonic of radiation is about 5%. This low level is achieved owing to the above-noted anchoring of the source to the underlying medium providing connectedness of the source with the medium: u≥0. Conversely, for the vibrator of the same type, CV-40, the presence of a subharmonic and higher harmonics is clearly defined. Initially this vibrator was developed as a mobile source and its anchoring to the underlying medium was not provided. For this reason the condition of connectedness of the source with the medium was not met, which results in well-defined effects of radiation nonlinearity. The subharmonic constitutes up to 40%, the second harmonic, up to 30%, and the third one, up to 20% of the fundamental harmonic. Thus, we have a clear radiation power redistribution on harmonics. For the hydroresonant vibrator HRV-50 (Fig. 1b) the second harmonic is well-defined at a level of 25% of the fundamental one. Here nonlinearity is determined by the nonlinearity of the air spring, which manifests itself as the oscillating liquid column moves up and down. Nonlinear radiation effects are least pronounced in the case of the CV-10/100 vibrator. Here a part of the radiation power goes to second, third, fourth, and fifth harmonics (Fig. 1d). The total power losses by harmonics do not exceed 20%.

The radiation nonlinearity effects recorded in the vibrator zone continue in the far zone, that is, at distances that are much greater than the wavelength of seismic oscillations. To estimate these effects, the relationships between the levels of vibrational seismograms obtained by convolution at main and second harmonics of the sounding sweep signal were compared. Specifically, for the CV-100 vibrator main frequencies of the sweep signal lie within 5.5…8.5 Hz, and of second harmonics, within 11…17 Hz.

Fig. 2 shows vibrational seismograms obtained with mutual-correlation convolution of reference sweep signals recorded at the Z-component in the above frequency ranges. These results correspond to two distances: 20 km and 50 km. The parameters of the seismograms are also given in Fig. 2. The amplitudes of dominant waves in discrete ADC units are also provided here. Peculiarities of the seismograms presented are as follows: P-waves are highly compact and well-defined in the zone of second harmonics. This is due to the fact that, in comparison to S-waves, the dominant spectrum of P-waves is concentrated in the zone of higher frequencies (in particular, in the frequency range of second harmonics). This peculiarity is observed at the both distances, namely, at 20 km and 50 km. In this case the contribution of second harmonics with respect to main constitutes about 3%.

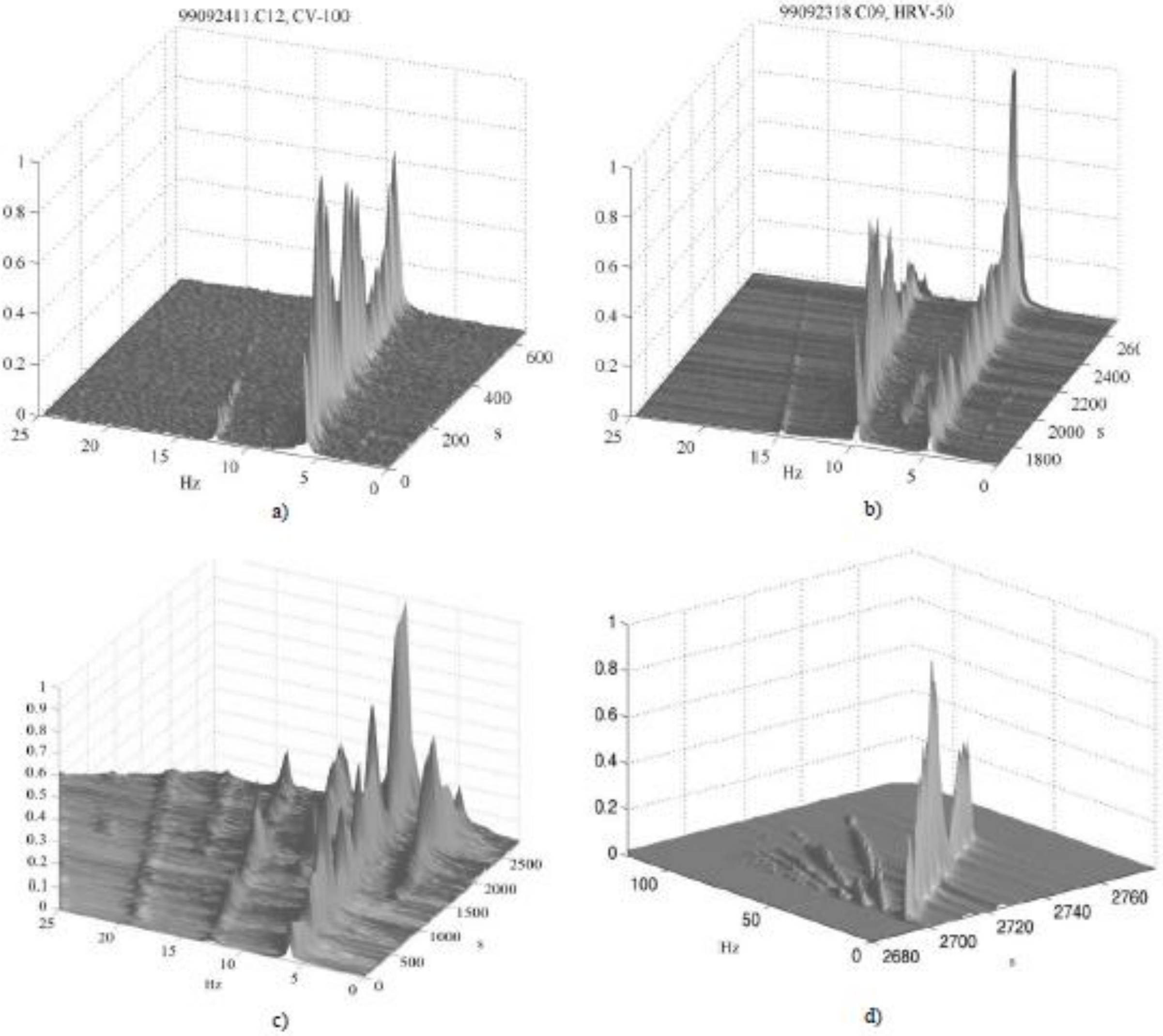

Fig. 1

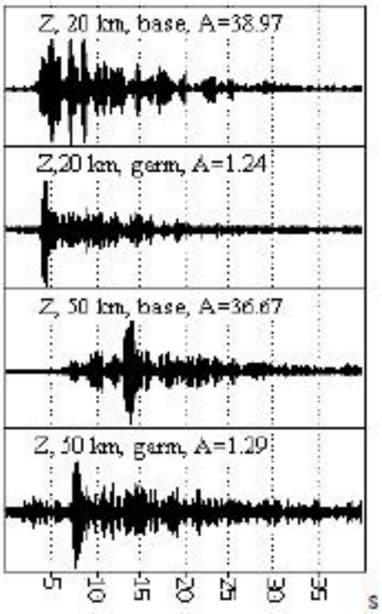

Fig.2. Vibrational seismograms for base and second harmonics at distances of 20 and 50 km

It should be noted that the measured levels of second harmonics at the X- and Y-components are less than 1%.

The nonlinearity effects of radiation from the CV-40 vibrator affect the character of seismograms (vibrational correlograms) obtained in the main (working) frequency band of sounding (7.91…11.23 Hz), at the subharmonics (half the working frequency band) and second harmonics (doubled working frequency band).

The results of these correlation convolutions characterizing vibrational seismograms for the Z-component are presented in Figs. 3a and 3c, respectively. The seismograms were obtained at distances from the source of 350 m…1185 m, and the spacing between the sensors was 200 m.

It follows from the figures that the most contrasted wave arrivals are at higher harmonics, which allows increasing the accuracy of measuring the wave arrival times.

The contribution of second harmonics of sounding signals to the levels of oscillations recorded in the near and far zones must be taken into account in studying nonlinear effects caused by the wave propagation medium.

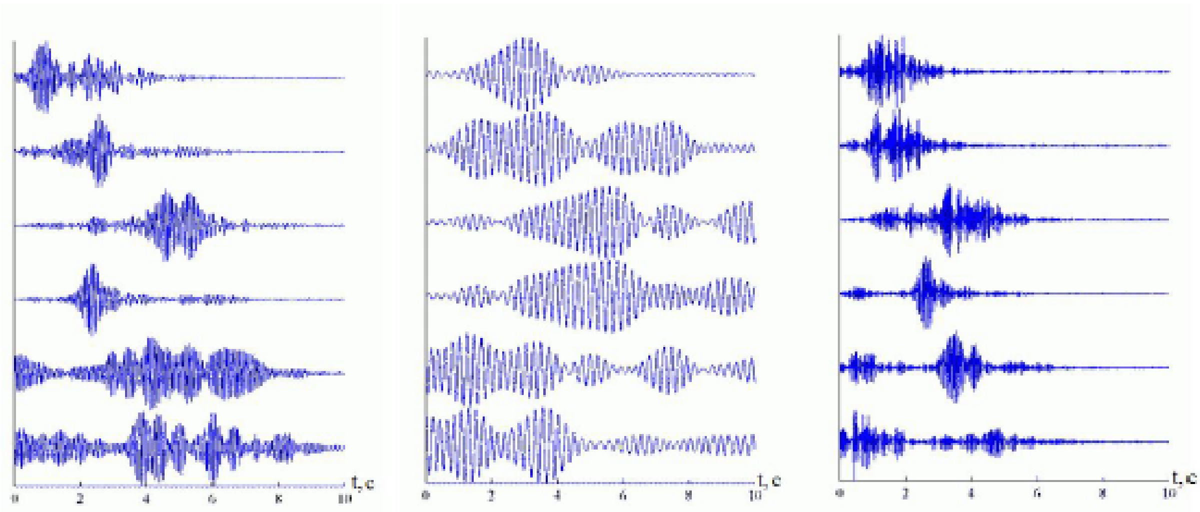

Fig. 3. Vibrational seismograms of CV-40 vibrator, obtained at distances of 350…1185 m for: a) – main frequencies 7.91–11.23 Hz; b) – subharmonics (3.95–5.61 Hz); c) – second harmonics(15.82–22.46 Hz).

As noted in Introduction, vibrators simultaneously generate various types of fields: main seismic, accompanying acoustic, electromagnetic, and electric ones. The radiation nonlinearity effects are also typical for these fields, as for seismic ones. The result of simultaneous recording of seismic, acoustic, and seismomagnetic fields radiated by the HRV-50 vibrator is illustrated by spectrograms of the corresponding signals recorded in monochromatic radiation modes at some fixed frequencies.

For instance, Fig. 3 presents the amplitude spectra of signals from the HRV-50 vibrator, recorded in the source near zone and of noise. The analysis was made in the frequency range of 0…25 Hz for the radiation mode at a main frequency of 6.4 Hz. It follows from the analysis of the results presented here and other results of measurements that nonlinear phenomena associated with the appearance of second harmonics of 12.8 Hz. can manifest themselves in all the three types of fields.

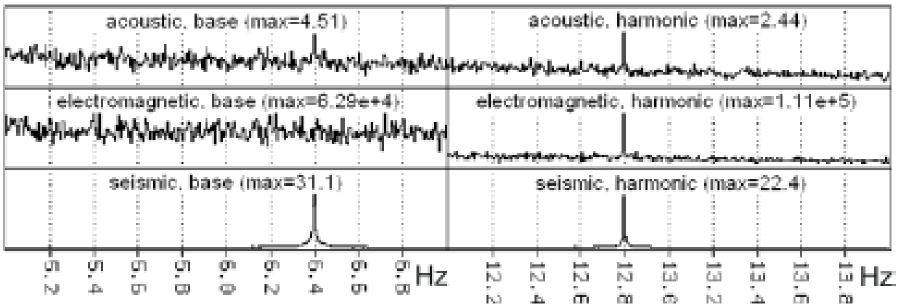

Fig. 4. Amplitude spectra of signals and noise for HRV-50 vibrator; main frequency: 6.4 Hz.

In some cases second harmonics can have higher noise immunity than main ones (Fig. 3). It is caused by the phenomenon of multipath propagation of monochromatic oscillations to the earth and the atmosphere leading to an interference of oscillations [10].

IV. Conclusions

1. In this paper, the problem of nonlinear dynamics of seismic vibrators of different types was considered. This problem is associated with analysis of nonlinear processes at the stage of excitation of waves of different nature, that is, seismic, acoustic, and electromagnetic ones.

2. It has been shown that the radiation nonlinearity effects recorded in the vibrator zone continue in the far zone, that is, at distances much greater than the wavelength of seismic oscillations. Study and consideration of these effects are of primary importance for increasing the reliability of interpreting experimental results in investigation of nonlinear processes in the medium by vibrational sounding.

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