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The nonlinear processes in active monitoring

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Abstract. One of the methods used to monitor the developing geodynamic processes in seismic-prone zones is based on the regular sounding of a medium by powerful seismic vibrators, with a subsequent analysis of the time dynamics of the seismic field parameters.

Such a monitoring is accompanied by certain nonlinear processes taking place at the stages of radiation and propagation of seismic oscillations. One of them is due to peculiarities of constructions of different vibrators and the processes of their interaction with the underlying surface. Other processes develop in a medium of seismic wave propagation. Such processes enrich a seismic wave field with additional lower and higher frequency components. In this paper, it is shown that the allowance for these processes increases the noise immunity of vibrational correlograms (analogs of explosive seismograms), as well as their time resolution, contributing to an increase in the accuracy of measurements of the arrival times types of the main wave types.

A modern concept of the earthquake source development is similar to that of development of a system of cracks. Broadening the spectra of the initial sounding seismic oscillations also results from the vibroseismic sounding of fractured dilatancy media typical of earthquake-prone zones. The applicability of parameters of the wave field nonlinearity in the form of possible prognostic characteristics of the earthquake source development is justified. The results of analysis and conclusions presented in this paper are based on numerical calculations and experiments.

The experiments were carried out when monitoring a 355-km long Earth's crust zone in the periods of the lunar-solar tides. It is shown that allowance for the ratios between high and first harmonics of seismic wave fields provides invariance of the positive results of monitoring with respect to inevitable seasonal and instrumental fluctuations of the intensity characteristics of the radiation field. At the same time, a high sensitivity of the relations to small variations of stresses in the Earth's crust is retained.

1. Introduction

The active vibroseismic monitoring of seismic-prone zones is aimed at following rheological characteristics of a medium when developing geodynamic processes preceding natural disasters and anthropogenic catastrophes. Such monitoring is based on a regular sounding of a medium by seismic oscillations of a recurrent form from low-frequency vibrators. Each act of sounding

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is a vibrosession. Analysis of the medium response parameters is made on the basis of the results of sounding [1, 2].

The identity of vibrosessions can be disrupted due to the influence of some interfering factors: seasonal factors associated with the freezing-thawing of the ground under a vibrator, instrumental errors affecting the intensity characteristics of the radiation field, etc. In this connection, there arises a problem of providing invariance of informative parameters of a seismic field with respect to these factors. On the other hand, it is known that vibrosessions are accompanied by nonlinear processes, which manifest themselves at the stages of radiation and propagation of vibroseismic oscillations.

The problem of development of nonlinear effects in the process of acoustic wave propagation in elastic isotropic media has been studied for several decades. In particular, a paper [11] dealt with investigation of nonlinear effects, which occur in an elastic isotropic medium under the effect of finite deformations and propagation of an elastic wave. This was considered by a calculation of the cubic terms in the elastic energy. It is shown that the interaction between longitudinal and transverse waves leads to the appearance of the second harmonics in the transverse wave. The paper [8] presents the basic order results of elastic theory by Murnaghan for the elastic wave propagation in isotropic solids and a summary of major results of nonlinear interaction of plane elastic waves. Important results on nonlinear effects in wave propagation theory in an elastic isotropic medium are presented in publications by other authors [3, 10, 14].

The processes of propagation of seismic oscillations when monitoring seismic-prone active zones are characterized by the fact that seismic waves are passing through nonlinearly elastic fractured media [9].

Problems of investigating the nature of nonlinear processes and obtaining numerical estimates of the results of their manifestations in fractured media are not only of a purely scientific interest, but also have practical applications aimed at increasing sensitivity and accuracy of vibroseismic monitoring technique. In connection with this problem, this paper describes some results of experimental investigations whose purpose is to estimate the nonlinear effects of radiation from some types of vibrators and propagation of seismic oscillations in a 335-km long Earth's crust area in the periods of lunar-solar tides. It is shown that the allowance for the ratios between high and first harmonics of seismic wave fields provides invariance of the positive results of monitoring with respect to inevitable seasonal and instrumental fluctuations of the intensity characteristics of the radiation field. At the same time, a high sensitivity of the relations to small variations of stresses in the Earth's crust is retained.

2. Nonlinear processes of radiation and vibroseismic oscillations processing

Sounding a medium is accompanied by manifestation of the two types of nonlinear processes: radiation and propagation. The nonlinear physical effects at the source-medium interaction result in occurrence of thelower and the higher harmonics in seismic oscillations. As an illustration, Figure 1 presents spectral-temporal functions of the oscillations radiated by the two types of vibrators [1]: the centrifugal vibrator CV-100 (Figure 1a) and the hydro-resonance vibrator HRV-50 (Figure 1b) with amplitudes of a disturbing force of 100 tons and 50 tons, respectively. In the first case, the presented spectrum is associated with oscillations with linear frequency modulation (the sweep signal) within 6.25–9.5 Hz and a duration of 600 s. In the second case, we have 5–7 Hz and 1400 s, respectively. In both cases, the nonlinear radiation effect is characterized by appearance of the second and the third harmonics in the spectra.

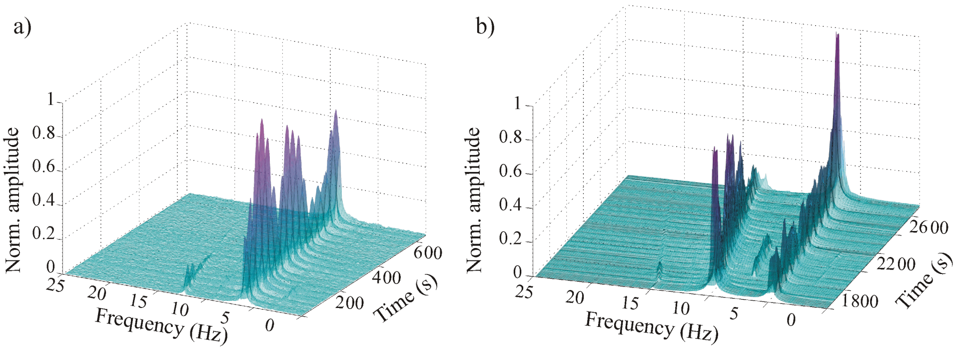

Figure 1. Spectral-temporal functions of oscillations radiated by centrifugal vibrator CV-100 (a) and hydro-resonance vibrator HRV-50 (b)

To estimate the level of nonlinear effects as related to the both types of sources, Figures 2a and 2b show the histograms corresponding to the ratios between the amplitudes of the second and the base harmonics (nonlinear coefficients) of the vibrators HRV-50 and CV-100, respectively, at the discrete radiation frequencies 6, 6.4, 6.5, 7.0, and 7.5 Hz. These ratios are calculated for the spatial coordinates x, y, z of the wave field, where x and y are horizontal components, and z is a vertical field component. One can see from the histograms that the level of nonlinearity at certain frequencies can attain 100 %. This effect is associated with some peculiarities of the construction of a specific type of a vibrational source, the failure to meet the condition of non-separability of this source with a medium, as well as with its mechanical properties [7].

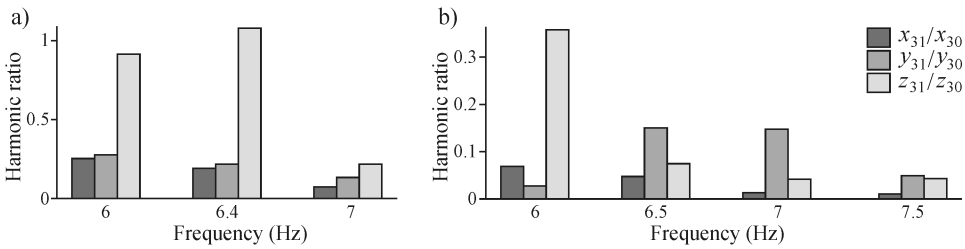

Figure 2

Below, we present the results of the data analysis with allowance for nonlinearity effects of the seismic wave field for the sounding mode with broadband oscillations. The algorithm of calculation of vibrational seismograms is based on the correlation convolution of the recorded seismic signals with a reference signal, which repeats the shape of the sounding signal from the oscillation source:

$$R(m) = \sum_{i=0}^{N} u(t_i)\,\nu(t_{i-m}), \quad m = 1, \dots, M. \tag{1}$$

Here $u(t_i)$ is a recorded seismic signal. The reference signal $\nu(t_i)$ is formed in the form of the functions $\nu_1(t_i) = A\cos(\omega_0 t_i + \beta t_i^2/2)$ and $\nu_2(t_i) = A\cos(2\omega_0 t_i + \beta t_i^2/2)$ and β is the frequency sweep rate.

In the case under consideration, the signal $\nu_1(t_i)$ is within the sounding range at basic frequencies (5.5–8.5 Hz) and $\nu_2(t_i)$ is at second harmonics (11–17 Hz). Thus, we obtain vibrational seismograms corresponding to different distances from the vibrator, namely, 0.3 km (Figure 3), 20 km, and 50 km (Figure 4). The parameters of the seismograms are given over each seismogram in the figures. Here, the amplitudes of dominant waves in discrete units of the analog-to-digital converter are additionally presented. Figure 3a presents the results of convolution in the frequency bands of 5.5–8.5 Hz (base frequency) and Figure 3b gives the results in the frequency bands of 11.0–17 Hz (second harmonics). Figure 4 presents the results of convolution of the same signals, but associated with the sounding at distances of 20 and 50 km. It is clear that seismograms of the second harmonics are characterized by a sharper arrival of the first (longitudinal) waves (5 s at 20 km, 7 s at 50 km), which increases the accuracy in measuring the arrival times of waves and their time resolution. From the point of view of seismic physics, higher contrast in the arrival of P-waves is due to the fact that they are saturated with high frequencies that are present in the second harmonics domain.

The level of nonlinear effects determined by the ratio between the maxima of the secondary and the base seismograms is about 3 %.

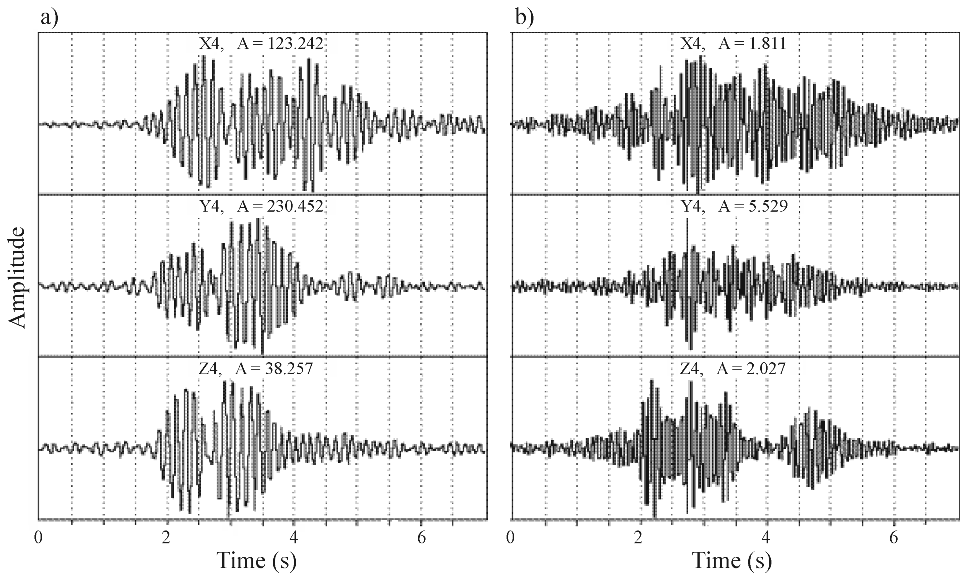

Figure 3. Vibrational seismograms for the base and the second harmonics at a distance of 0.3 km

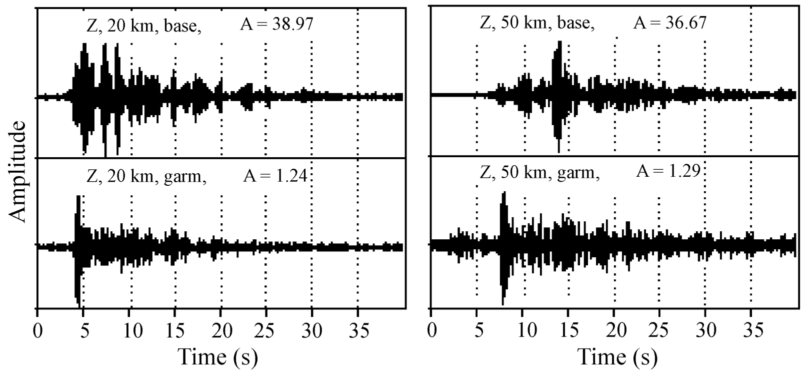

Figure 4. Vibrational seismograms for the base and the second harmonics at distances of 20 and 50 km

3. Increasing the accuracy in determining wave arrival times in vibrational seismograms with nonlinear processing

In the technology of deep vibroseismic sounding (DVS) of the Earth, there are some difficulties in determining the wave arrival times in vibrational seismograms obtained from a source located at a distance of hundreds of kilometers. The difficulty is due to the following two factors: the limited power and the range of work frequencies of vibrators in comparison to powerful explosions. Here, the influence of external noise on the process of recording seismic oscillations manifests itself to a considerable degree. One of the classical ways of avoiding these difficulties is a synchronous summation of vibrograms (vibrational seismograms) along the lineup axes and over a series of repeating sounding sessions [4]. In this case, the dependence of the amplitude of the total wave on the direction of summation creates an effect of directional sensitivity which, by analogy with antennas, can be called directional characteristic (DC). An attempt to increase the accuracy of determining the wave arrival time in vibrational seismograms with a limited number of seismic receivers ($n \approx 5$) brings up an idea of using the principle of nonlinear processing, which forms the basis of the multiplicative antenna. In this case, in contrast to antennas with linear processing, one can obtain a more accurate resolution in the wave propagation direction with the same number of antenna elements. In the case of n sensors, the output signal is as follows:

- for nonlinear processing:

$$u_{\Pi} = \overline{u_1 \cdot u_2 \cdots u_n} \approx F_e^n \cdot \Psi_1(k, \theta, d) \tag{2}$$

- for linear processing:

$$u_{\Sigma} = \overline{u_1 + u_2 + \ldots + u_n} \approx n \cdot F_e \cdot \Psi_2(k, \theta, d), \tag{3}$$

where F_e is a sensitivity characteristic in the DC direction of one sensor, θ is the angle between the direction of wave arrival and the perpendicular to the line of seismic receivers, $k = 2\pi/\lambda$ is the wave number, d is one step of the adjacent sensor located at a distance.

Obviously, vibrational seismograms obtained as a result of correlation convolution (1) correspond to the zero phase signal and, hence, its arrival time is determined by a maximum wave amplitude. The variance of the wave arrival estimate in the direction of propagation θ is determined by the second derivative [12] in the form $D_\theta = -1/(d^2 u(\theta)/d\theta^2)\big|_{\theta_0}$, where θ_0 corresponds to the greatest sensitivity of the recording seismic receivers achieved in the direction of the wave front propagation. The algorithm of the search for this direction is based on the calculation of $u_{\Pi}^* = \max u_{\Pi}$ on a set of linear travel time curves, whose angular location is within the angular window initially chosen with allowance for the expected wave velocity. In this case, the calculation is made using the exhaustive method. For a particular case, when $\theta_0 = 0$ (perpendicular wave front incidence) $F(\theta_0) = 1$, at $n \gg 1$ for nonlinear processing, D_{θ_1} has the order $\sim -1/n^2$, and for linear processing, the order $D_{\theta_2} \sim -1/n$. Thus, the error in determining the wave propagation direction, determined by the direction of the travel time curves of vibrational seismic traces, for nonlinear processing (2) is by a factor of n smaller than that for linear processing (3).

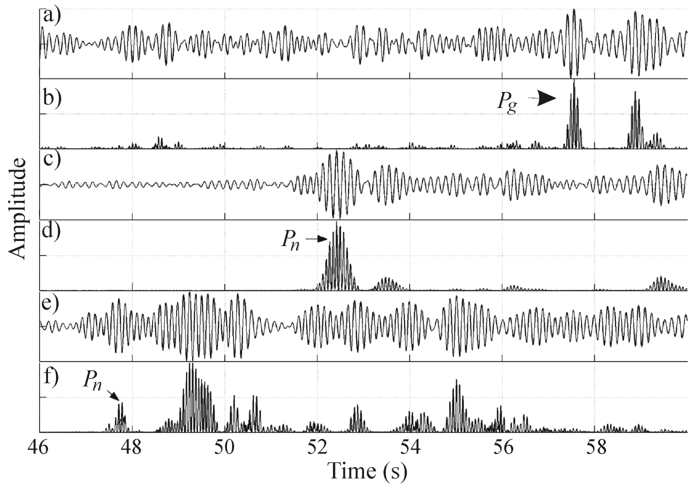

Figure 5. Seismograms with linear (a, b, c) and nonlinear (d, e, f) processing

A high resolution of the nonlinear approach is illustrated for the processing of vibrational seismograms obtained from the vibrator CV-100 at DVS in the Degelen–Bystrovka direction (Figure 5).

The recording points were located at distances of 304, 342, and 371 km from the source. The sounding was carried out by sweep-signals in the frequency range of 5.85–8.0 Hz with a frequency sweep duration of 31 min 29 s.

At the top of Figure 5, one can see seismograms at the distances of a) 371 km, b) 342 km, and c) 304 km obtained by linear summation of seismic traces along travel time curves corresponding to the waves refracted from the Moho boundary (V_P = 8.1 km/s). At the bottom of Figure 5, seismograms are for the distances of d) 371 km, e) 342 km), and f) 304 km obtained by the nonlinear processing of the same vibrational seismograms as in the case of the linear processing. A comparison of the results of both types of processing shows that in the second case, the contrast of arrivals of P_n-waves and the sharpness of their maxima is greater than in the first case. For these distances, the arrival times t_p are 56, 52.5, and 47.6 s, respectively.

4. The nonlinear processes in the source zones monitoring

Modern concepts of the earthquake source preparation based on the kinetic theory of destruction developed by S.N. Zhurkov [15] and the multidisciplinary approach by A.S. Alekseev [2] consider the development of a system of cracks resulting from the growth of the volume density of microcracks in the destruction zone. On this basis, in [2] it was proposed to use a space-time function $\Theta(x, y, z, t)$, with the help of which one can try to approximately describe the density of cracks in a medium.

The seismic method of observing longitudinal and transverse waves from powerful vibroseismic sources with high metrological characteristics of amplitude, frequency, and phase of oscillations generated in a medium can provide more detailed data about its structure with a time-varying fracturing. It was proved for the recorded wave field in the far zone [1] that the dynamic characteristics of the wave field are most sensitive to changes in the characteristics of the medium elasticity. There is an additional argument for the use of these characteristics: the medium fracturing is a physical basis for the development of nonlinear processes of propagation of seismic oscillations in source zones. This shows that the parameters of nonlinearity of the wave field that causes the appearance of high harmonics (enriching the initial sounding monochromatic oscillation), should be taken into account [6]. With allowance for this, it is important to relate the characteristics of the wave field nonlinearity and the parameters of medium fracturing.

In [13], such a dependence was obtained for a model of fracturing that develops in a homogeneous and isotropic medium with the module of elasticity K_1, μ_1 and the density ρ_1. The uniformly scattered and chaotically oriented voids of a spheroidal shape are taken as initial model of fracturing. The shape of the voids is determined by the parameter α, which is equal to the ratio between the rotation axis length of a spheroid and the length of its second axis. The distribution of the relative volume of voids between its minimal value $\alpha_{\min}$ and maximal value $\alpha_{\max}$ is described by the function $\varphi(\alpha)$. It is assumed that the length of an elastic wave with the highest frequency propagating in the medium simulated is much greater than the linear dimensions of the largest voids.

The equation of propagation of plane monochromatic elastic waves along OX-axis in the medium simulated, when only longitudinal motions are present in this medium ($u_x \neq 0$, $u_y = u_z = 0$) is as follows:

$$\rho_0 \frac{\partial^2 u_x}{\partial t^2} - M_0 \frac{\partial^2 u_x}{\partial x^2} = B \frac{\partial u_x}{\partial x} \frac{\partial^2 u_x}{\partial x^2}. \tag{4}$$

At the boundary condition $u_x(0,t) = U_x \sin \omega t$, the solution to the equation in a second approximation has the following form [13]:

$$u_x = U_x \sin \omega \Big(t \mp \frac{x}{c_P} \Big) - \Big(\frac{U_x}{2} \Big)^2 \frac{B}{M_0} k_P^2 x \cos 2(\omega\, t \mp k_P x), \tag{5}$$

where

$$k_p = \omega / c_p, \quad B = -3\varphi_{ot} \frac{k_0}{p_0} \Big(a \frac{k_0^2}{k_1} + \frac{4}{3} b \frac{\mu_0^2}{\mu_1} \Big) f(\alpha_0), \quad M_0 = k_0 + \frac{4}{3}\mu_0.$$

The following relations for the effective elasticity module of the medium with spheroidal voids are used:

$$K_{(1)} \approx K_0\left[1 - \varphi_{ot} a \frac{K_0^2}{p_0 K_1} f(\alpha_0) u_{ll}\right],$$

$$\mu_{(1)} \approx \mu_0\left[1 - \varphi_{ot} b \frac{K_0 \mu_0}{p_0 \mu_1} f(\alpha_0) u_{ll}\right].$$

Here

$$K_0 \approx K_1 (1 + \varphi_{ot} a F)^{-1}, \quad \mu_0 \approx \mu_1 (1 + \varphi_{ot} b F)^{-1},$$

$$a = \frac{4(1-\nu_1^2)}{3\pi(1-2\nu_1)}, \quad b = \frac{8(1-\nu_1)\cdot(5-\nu_1)}{15\pi(2-\nu_1)},$$

$$f(\alpha_0) = \frac{\varphi(\alpha)}{\varphi_{ot}}, \quad F = \int_{\alpha_0}^{\alpha_{\max}} \frac{f(\alpha)}{\alpha}\, d\alpha, \quad \varphi_{ot} = \int_{\alpha_0}^{\alpha_{\max}} \varphi(\alpha)\, d\alpha;$$

φ_{ot} is the initial value of the medium fracture porosity; ν_1 is Poisson's coefficient, K_0 is the effective compression modulus of the microfractured medium, and u_{ll} is the sum of diagonal components of the dynamic deformation tensor.

It follows from (5) that in a fractured medium there appear harmonics of doubled frequency. Their level is determined by the coefficient B, which depends on the character of the medium fracturing, the Mach number $M = U_x\omega/c_p$, and the wave travel length x, in which case the level of the second harmonic increases proportionally with x. This phenomenon was earlier noted as accumulating nonlinearity in a nonlinearly elastic medium. With allowance for (5), the coefficient of nonlinearity of the monochromatic wave shape, determined by the ratio between the amplitudes of the base and of the second harmonics, is as follows:

$$\frac{u_2}{u_1} = \frac{1}{8}\frac{U_x B k_P^2 x}{M_0}. \tag{6}$$

Equation (6) relates parameters of the wave field nonlinearity in the destruction source zone and the medium fracturing determined by the parameter B, which depends on the sizes of fractures and their distribution density, as well as on the medium elasticity modulus. Taking into account this dependence and the modern concept of the earthquake destruction source development as a system of cracks, it seems that the dynamic parameters of wave field nonlinearity can be successfully used as a prognostic parameter that characterizes this process.

According to equation (6), an analysis of the nonlinearity coefficient as a function of the characteristics of the medium fracturing, the amplitude of oscillation velocity U_x of medium particles, and the distance x was made. The water-saturated fractured granite with the following elasticity parameters was chosen as medium: Young's modulus $E = 2.216 \cdot 10^9$ Pa, the Poisson coefficient $\nu = 0.442$, the static pressure $p_0 = 10^3$ Pa, the frequency

$f = 10$ Hz, and the propagation velocity of P-wave in granite $C_p = 2500$ m/s. For these parameters, in Figure 6, diagrams 1 and 2 show the nonlinearity coefficient of the monochromatic wave shape versus the ratio between the ellipsoid axes describing an elementary fracture. In the process of construction, the axes were given by the parameters $d_{\min}$, $d_{\max}$, and d_{vert}. The first two parameters correspond to minimal and maximal horizontal sizes of spheroids, and d_{vert} is the linear vertical size.

A change in the ellipsoid sizes is described by a function of the form $\varphi(\alpha) = 1/\alpha$, where α varies from $\alpha_{\min} = d_{\min}/d_{\text{vert}}$ to $\alpha_{\max} = d_{\max}/d_{\text{vert}}$. Diagrams 1–4 in Figure 6 consist of successively connected sections I, II, and III with the following sets of parameters: $\alpha_{\min} = 1$, $\alpha_{\max} = 10$; $\alpha_{\min} = 12$, $\alpha_{\max} = 50$; and $\alpha_{\min} = 52$, $\alpha_{\max} = 150$.

Diagrams 1, 2 were constructed for the path length $x = 10$ km, diagrams 3, 4 — for $x = 100$ km. The vibroseismic oscillation velocity of the medium particles $U_x = 30 \cdot 10^{-9}$ m/s corresponds to diagrams 1 and 3, and the velocity of $70 \cdot 10^{-9}$ m/s corresponds to diagrams 2 and 4.

Another relation for the "accumulation" of the nonlinear effect in media with dissipation and absorption is determined by the dependence of the second harmonic amplitude on a distance described by the relation [14]

$$a_2 = \frac{K_c x \omega^2 a_1^2}{8c_{p,s}^2}. \tag{7}$$

Here x is the wave path length, K_c is the nonlinearity coefficient of the medium determined by the expression $K_c \approx \rho\nu(\Delta\nu/\Delta p) \approx (\Delta\nu/\nu)\Delta\theta$, in which ρ is the density, $\Delta\theta$ is a volume deformation variation, Δp is a pressure variation, a_1 is the amplitude of the first harmonic, and $c_{p,s}$ is the velocity of P- or S-wave. The value of this coefficient is $K_c \approx 10^3$. As an illustration, Figure 7 presents diagrams for the nonlinear effect "accumulation" versus a

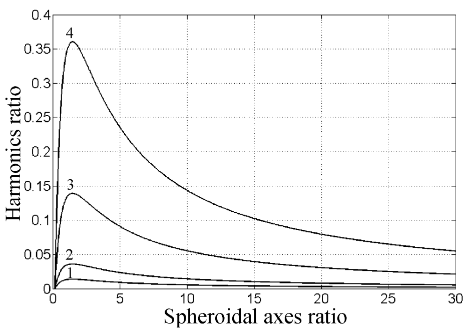

Figure 6. The ratio between the second and the first harmonics versus the geometrical parameters of the medium inhomogeneity

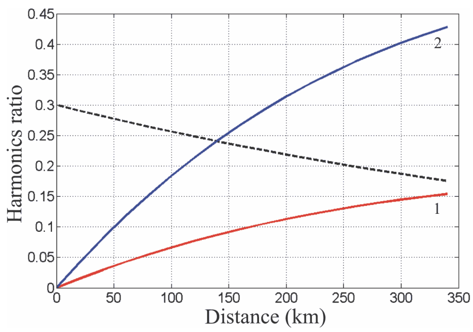

Figure 7. Coefficient of nonlinear distortions versus a distance at different seismic velocities

distance at given seismic velocities in a “source-receiver” distance range of $0.3 \div 355$ km.

It follows from an analysis of Figures 6 and 7 that the ratio between the second and the first harmonics can increase several times as the wave travel path increases. The presence of maxima in the diagrams (see Figure 6) probably indicates to the fact that nonlinear effects of wave propagation predominate in inhomogeneous media with limited linear sizes of inhomogeneities.

The nonlinearity parameters of the wave field in the far zone are subject to the influence of the nonlinearity effect of radiation by the vibrator [5]. Changes in the initial ratios between the second and the base harmonics a_{02}/a_{01} observed in the destruction source zone, depending on distance, vary according to the following law:

$$\frac{a_{f_2}(r)}{a_{f_1}(r)} = \frac{a_{02}}{a_{01}} \exp[(\alpha_2 - \alpha_1)(r - r_0)], \tag{8}$$

where $\alpha_{1,2} \approx 2.5 \cdot 10^{-4} f_{1,2}$ km^{-1} is the medium absorption coefficient due to non-ideal elasticity, and r_0 is a “source-receiver” distance near to the source zone.

As an example, the dashed line in Figure 7 shows attenuation curve (8) for the cases when $f_1 = 6.3$ Hz and $f_2 = 12.6$ Hz. It follows from the presented curves and (7) that the development of nonlinear processes is primarily associated with low-velocity waves, which include, in particular, S-waves.

5. Results of experimental research

The manifestation of the nonlinearity effect was estimated with monochromatic signals on the basis of the amplitude ratios of the second and the base harmonics of oscillations. The spectrograms for the mixture of useful monochromatic signals and noise confirm the possibility of detecting both types of harmonics at a “source-receiver” distance of 355 km (in this case, the signal of the base harmonics at a frequency of 6.3 Hz and that of the second harmonics at 12.6 Hz), presented in Figures 8a and 8b, respectively.

The parameters of the spectra are shown in the upper part of the figures: m is the amplitude of the spectral peak at the frequency f and ρ is the ratio between the amplitude m and the root-mean-square value of noise.

It follows from the spectrograms that the ratio between the maxima m of both signals is $243.4/501.4 = 0.48$. At the same time, calculated relation (8) at this distance and frequency is 0.14. The difference is determined by the contribution to the nonlinearity effect from the medium where oscillations propagate.

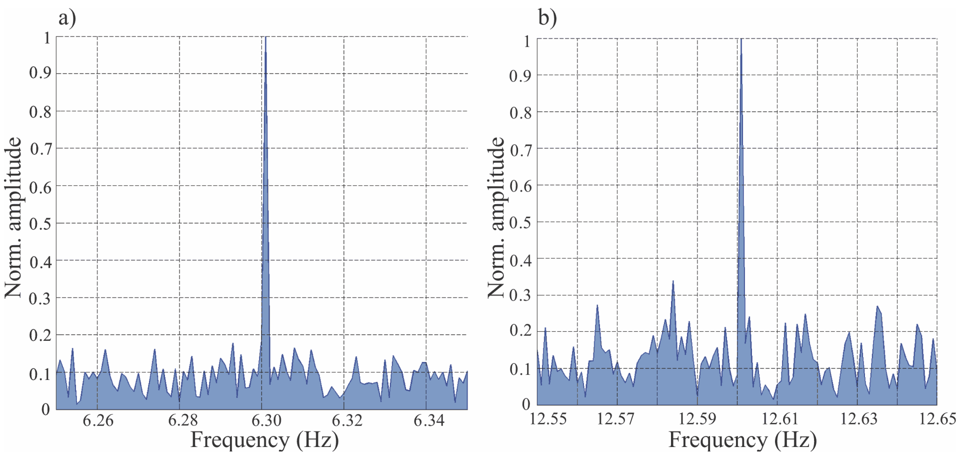

Figure 8. Spectrograms of the base (a) and the second (b) harmonics at a distance of 355 km

It seems natural to take into account the contribution of high harmonics to the informative index characterizing the dynamics of geodynamic processes in the medium and, first of all, in seismic-prone zones. The effectiveness of using these parameters is illustrated below for the geodynamic processes developing in the Earth's crust during the lunar-solar tides. The amplitude ratios of the second and the base harmonics of oscillations were recorded in the course of Earth's soundings with the help of repeating (with a period of three hours) sessions of sounding by monochromatic oscillations, which were generated by a powerful seismic vibrator of the type CV-100. Each session consists of sequentially radiated 20-minute oscillations at frequencies of 6.3 and 7.0 Hz. These sessions were continuously repeated during 96 hours. The main objective of the experiment is described in detail in [4]. This paper investigates the possibilities of selecting a daily and a half-daily periodicity in variations of the seismic field parameters for the lunar-solar tides. The time series as estimates of the amplitudes of the base and the second harmonics of oscillations, as well as their interrelations, were constructed with the use of the results of pre-processing of the seismic signals records. Here, recordings with the components X, Y, Z were used. The corresponding results of data processing are the stages illustrated in Figures 9 and 10. In these figures, the abscissa axis represents the session number, and the ordinate axis shows values of the ratios between harmonics.

As a comment to the diagrams presented, we should note that those in Figure 9 reflect the ratios between the second harmonic of radiated oscillations and the base one at frequencies of 6.3 and 7 Hz. These data correspond to parameters of the radiated seismic field in the immediate vicinity to the source (at a distance of 30 m). It is seen that the greatest nonlinear effect

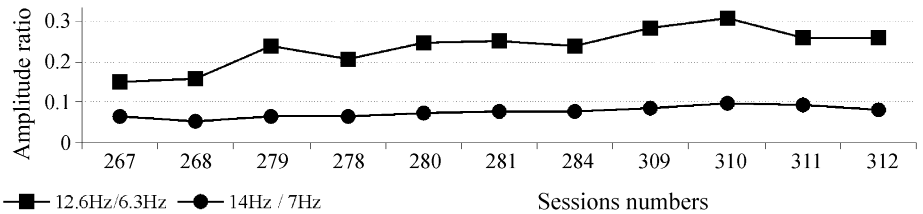

Figure 9. The ratio between the second and the base harmonics in the source. Sessions: 267–312

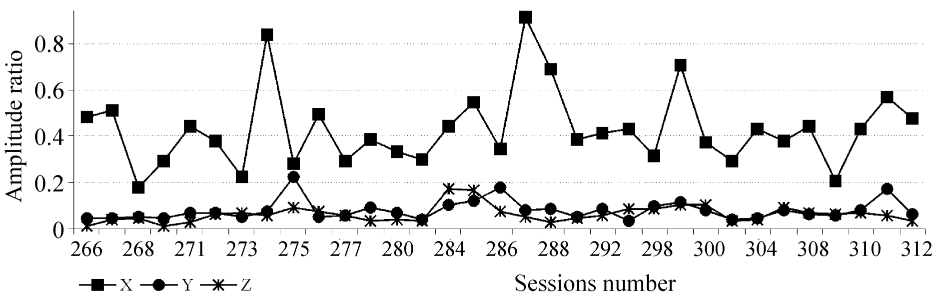

Figure 10. The ratio between the second (12.6 Hz) and the base (6.3 Hz) harmonics at the 5th gauge. Sessions: 266–312

manifests itself at a sounding frequency of 6.3 Hz. Here, the ratio of harmonics varies within 15–30 %, a sounding frequency of 7.0 Hz being within 5–10 %.

Figure10 shows similar ratios obtained at the receiving point at a distance of 355 km from the source corresponding to the components X, Y, Z and the sounding frequencies of 6.3 and 7.0 Hz, respectively. It follows from the analysis of the obtained diagrams that the greatest values of the ratios are with the components X and Z. Their values at different frequencies of sounding are different. If these data are compared to those observed near the source, it becomes obvious that the ratios of harmonics at such a distance are, on average, higher. In particular, we have 45 % against 7.5 % at 7.0 Hz and 50 % against 25 % at 6.3 Hz. The external noise affects fast fluctuations of the ratios obtained (from session to session).

Obviously, the observed increase of the nonlinear effect should be related to the contribution of the nonlinear processes of propagation of seismic oscillations to the medium. It follows from this assumption that in the multidaily dynamics of the nonlinear process, its connection with deformation processes in the medium due to the lunar-solar tides should manifest itself. It is known [16] that these processes are characterized by a daily and a half-daily periodicity. Latent periodicity in the series was selected with the use of the discrete Fourier transform employing the weight function to smooth the edges of the observation series.

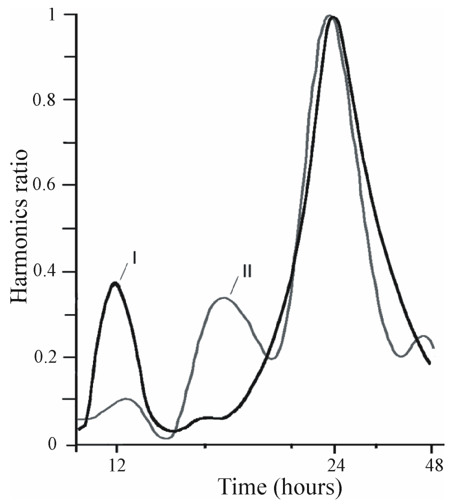

Figure 11. Levels of radiated signals

The results of this selection for the observation series corresponding to the ratios between amplitudes of the second and the first (base) harmonics with sounding frequencies of 6.3 are presented in Figures 11 (curve II). This curve is for the observation series corresponding to the component Z. For comparison, the diagram shows the amplitude spectrum of gravitational variations fixed in the same period (curve I). It follows that the daily periodicity is confidently distinguished within the time series $a_{12.6}(355)/a_{6.3}(355)$. The half-daily periodicity is weakly expressed.

An advantage of the monitoring method proposed is its invariance with respect to fluctuations of the radiated oscillations amplitude due to the season, instrumental factors, etc. This was experimentally confirmed by a comparative analysis of test recordings of radiated oscillations near the source, as well as of the ratios between amplitudes of the secondary and the base waves at a distance of 355 km. Graphs of the amplitudes of the base harmonics close to the source depending on the session number (at a frequency of 6.3 Hz and the components X, Y, Z) are presented in Figure 12. One can see in this figure that some of the sounding sessions characterize a sharp decrease in the oscillations levels caused by an "artificial" decrease in the perturbation force amplitude of the original source-vibrator CV-100. Despite this fact, the stability of the process of detecting half-daily and daily periodicities at the remote recording point due to terrestrial tides was

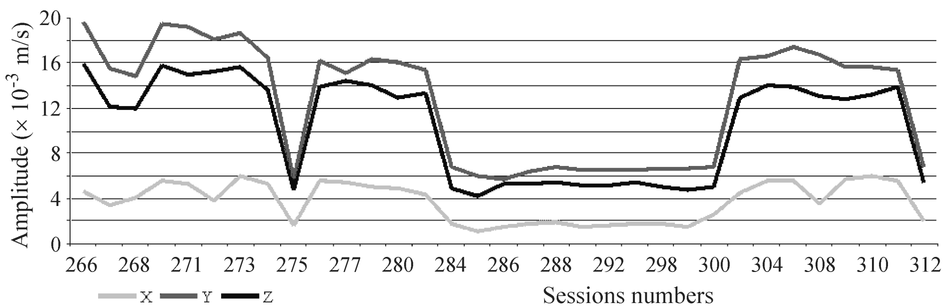

Figure 12. The ratio between the second (14 Hz) and the base (7 Hz) harmonics at the 5th gauge. Sessions: 266–312

retained. However, the above periodicities are not distinguished in the amplitude graphs under the conditions of source radiation with allowance only for the base harmonic at a frequency of 6.3 Hz. The reason for this is clear: fluctuations of the radiation oscillations levels bring about the corresponding fluctuations of the signal levels at the receiving point. At the same time, when the property of the ratio between the second and the first harmonics is taken into account (see Figure 9), it appears possible to detect the daily and the half-daily periodicities.

6. Conclusion

1. The problem of increasing the information content when processing seismic monitoring data with allowance for the nonlinear effects of wave fields at the stages of radiation and propagation of seismic oscillations in elastic media is considered.
2. The quantitative nonlinear characteristics are estimated for radiation and propagation of the seismic wave fields generated by powerful ground-based vibrators.
3. A statistical algorithm for the processing of observational data based on the measurement of amplitudes of the second and the base harmonics of seismic oscillations against noise and for calculation of their ratios is proposed.
4. The invariance of the algorithm proposed to variations of the force characteristics of radiation and high sensitivity to variations of the rigidity parameters of a medium due to geodynamic processes are proved. This is especially important for problems of the long-term tracing of processes of preparation of disasters in seismic-prone zones.

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