Bull. Nov. Comp. Center, Math. Model. in Geoph., 10 (2005), 19–33

Increasing of sensitivity of active vibroseismic monitoring method with allowance for wave field nonlinearity

M.S. Khairetdinov

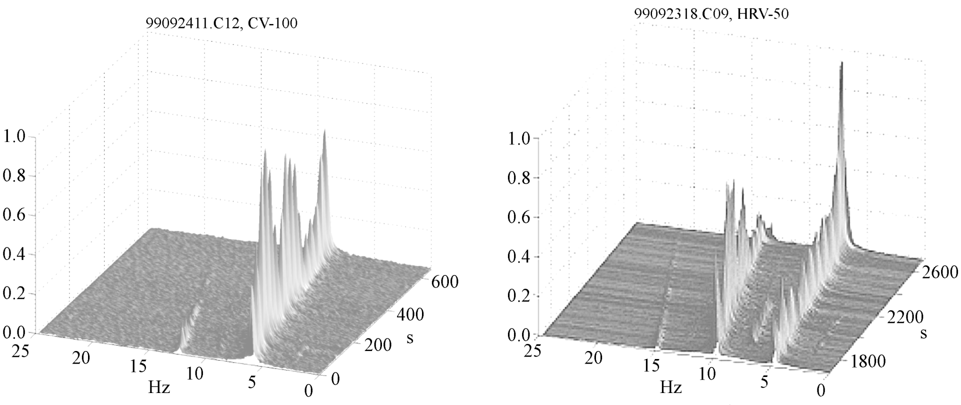
Abstract. Nonlinear wave processes of radiation and propagation of elastic oscillations in complex subsurface geometries are analyzed in terms of their role in improving the quality of seismic monitoring of geodynamic processes. The efficiency of this approach is illustrated by measuring parameters of seismic waves and analyzing their temporal dynamics with allowance for the lunar-solar tides.

Introduction

Analysis of regularities of propagation of wave fields in elastic media under the influence of external and internal factors is of importance when solving many scientific problems. Thus, when analyzing the influence of lunar-solar tides on such processes in the Earth, the solar and lunar gravity forces play the role of external factors. Nonlinear effects, which manifest themselves in this case as internal factors, are evolving at the stages of radiation and propagation of seismic wave fields, the latter being generated by various sources of seismic oscillations. Studying the nature of such processes and obtaining numerical estimates of the results of their manifestation are not only of merely scientific interest, but also of practical importance. This paper presents combined results of analysis of nonlinear processes of radiation, propagation, and processing of seismic oscillations generated by powerful vibrational sources. They will be used to increase sensitivity of the vibroseismic method of monitoring of geodynamic processes that take place at the stages of preparation of high-power natural disasters, such as earthquakes, volcano eruptions, etc.

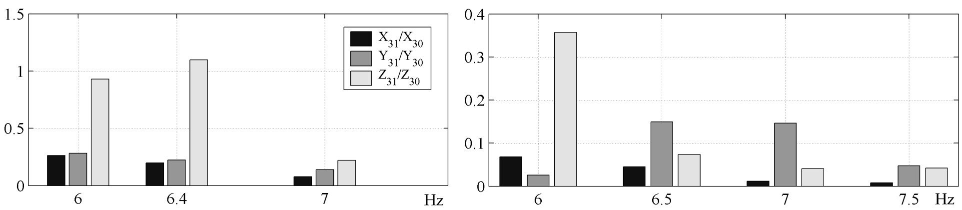
1. Nonlinear processes of radiation and processing of vibroseismic oscillations

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 the lower and the higher harmonics in seismic oscillations. As an illustration, Figure 1 presents spectral-temporal functions of oscillations radiated by two types of vibrators: the centrifugal vibrator CV-100 (Figure 1a) and the hydro-resonance vibrator HRV-50 (Figure 1b) with amplitudes of disturbing force



a b

Figure 1



a b

Figure 2

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.

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) 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 the horizontal components, and z is the 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 constructing a specific type of vibrational source, the failure to meet the condition of nonseparability of this source with a medium, as well as with its mechanical properties (see [1] for details).

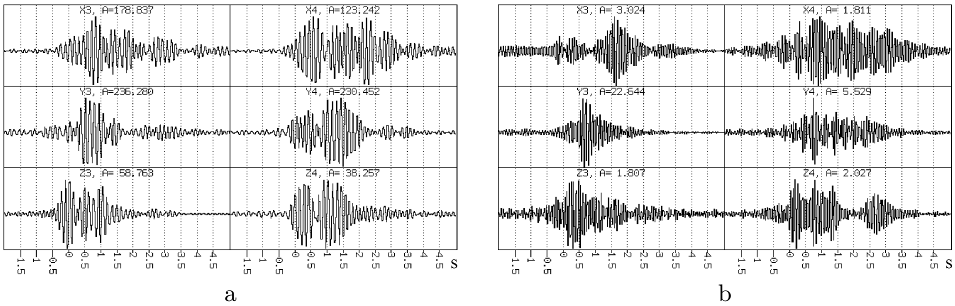


Figure 3. Vibrational seismograms for the base (a) and the second (b) harmonics at the distance of 0.3 km

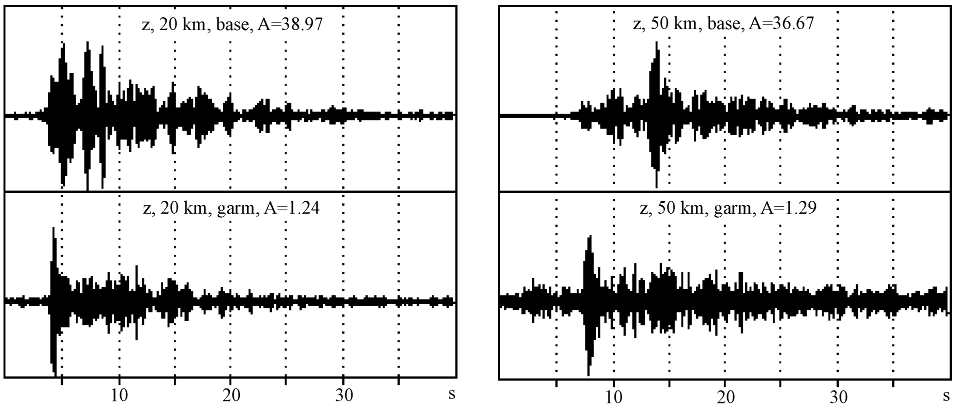


Figure 4. Vibrational seismograms for the base and the second harmonics at the distance of 20 and 50 km

We present the results of 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 the reference signal, which repeats the shape of the sounding signal from the oscillation source [2]. With the help of this algorithm, we simultaneously calculated vibrational seismograms in the bands of the base sounding frequencies and their second harmonics. Figure 3a presents the results of convolution in frequency bands of 5.5–8.5 Hz (the base frequency) and Figure 3b gives the results in frequency bands of 11.0–17 Hz (the second harmonic). These results are associated with the sounding at a distance of 0.3 km. 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 (4.8 s at 20 km, 7.8 s at 50 km), which increases the accuracy in measuring the arrival times of waves and their time resolution.

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

2. Increasing the accuracy in determining wave arrival times in vibrational seismograms by nonlinear processing

It is known that 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. One of the classical ways of avoiding these difficulties is synchronous summation of vibrograms along the lineup axes and over a series of repeating sounding sessions [3]. 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 a directional characteristic (DC). An attempt to increase the accuracy of determining the wave arrival time in vibrational seismograms at a limited number of seismic receivers ($n \approx 5$) brings up the idea of using the principle of nonlinear processing, which forms the basis of the multiplicative antenna [4]. In this case, in contrast to antennas with linear processing, one can achieve more accurate resolution in the direction of wave propagation at the same number of antenna elements. In particular, let $u_1 = F_e \cos \omega t$ be a signal at the output of the first sensor and $u_2 = F_e \cos(\omega t + kd \sin\theta) = F_e \cos(\omega t + \tau)$ be a signal at the output of the adjacent sensor located at a distance of one step d. Here F_e is the 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, and $k = 2\pi/\lambda$ is the wave number. Then

$$u_\Pi = \overline{u_1 \cdot u_2} = \lim_{T\to\infty} \frac{1}{T} \int_0^T u_1 u_2 \, dt = F_e^2 \cos(kd \sin\theta). \tag{1}$$

In the case of linear processing

$$u_\Sigma = \overline{u_1 + u_2} = F_e(\theta) \cos\Big(\frac{kd}{2} \sin\theta\Big), \tag{2}$$

that is, a maximum increase in sensitivity is by a factor F_e.

In the case of n sensors,

$$u_\Pi = \overline{u_1 \cdot u_2 \cdots u_n} = F_e^n \Psi_1(k, \theta, d), \tag{3}$$

$$u_\Sigma = \overline{u_1 + u_2 + \ldots + u_n} = n F_e \Psi_2(k, \theta, d). \tag{4}$$

It is known that for vibrational seismograms obtained as a result of the medium sounding by sweep signals, the shape of the wave corresponds 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 [4] in the form $D_\theta = -\left(\frac{d^2u}{d\theta^2}\right)^{-1}\Big|_{\theta=\theta_0}$, where θ_0 corresponds to the greatest sensitivity of the recording seismic receivers attained 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 an 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) $F(\theta_0) = 1$ and $n \gg 1$, $D_\theta \sim -1/n^2$ for the nonlinear processing and $D_\theta \sim -1/n$ for the linear processing. Thus, the error in detecting the wave propagation direction, determined by the direction of travel time curve of vibrational seismic traces, for nonlinear processing (3) is by a factor of n smaller than for linear processing (4).

The effectiveness of the nonlinear approach is illustrated on the processing of vibrational seismograms obtained from the CV-100 vibrator 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 made 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 371, 342, and 304 km obtained by the linear summation of seismic traces along travel time curve corresponding to the waves refracted from the Moho

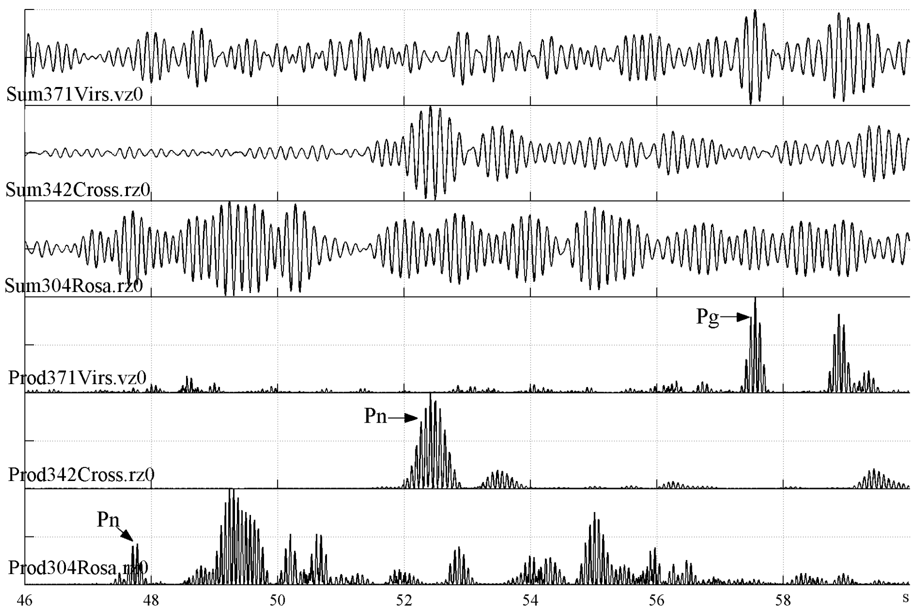


Figure 5. Comparison of linear and nolinear processing of seismograms

boundary ($V_P = 8.1$ km/s). At the bottom of Figure 5, the seismograms at the distances 371, 342, and 304 km are obtained by nonlinear processing of the same vibrational seismograms as in the case of linear processing. A comparison of the results of the 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.

3. Nonlinear processes of propagation of seismic oscillations

The propagation of seismic oscillations in a medium at distances much longer than their wavelength is also characterized by the appearance of higher harmonic components in the spectrum of a signal. Under certain conditions, these processes can essentially manifest themselves even in the propagation of waves of small deformations in the Earth, for which the principle of linear approximation is commonly used. This phenomenon can be proved, with allowance for [6], for the process of propagation in an inhomogeneous medium of a simple one-dimensional wave $u(x,t)$ described by the equation

$$\frac{\partial u}{\partial t} + Lu = -\varepsilon u \frac{\partial u}{\partial x}. \tag{5}$$

Here ε is the nonlinearity parameter, and L is the linear operator corresponding to the determined dispersion of linear waves. The nonlinearity parameter is estimated as $\varepsilon = v/c$, v is the amplitude of the velocity of particle oscillations in the medium, and c is the phase velocity.

Generally, the condition of smallness of the parameter ε, i.e., $\varepsilon \ll 1$, is necessary, but not sufficient for providing a linear approximation. The quantitative characteristics of the nonlinearity effect in the medium are affected by the processes of energy dissipation and wave dispersion. Let a medium with wave dispersion be characterized by the dispersion ratio $\omega_k = \omega(k)$, which describes the dependence of the oscillation frequency on the wave number k. It is known that the Earth, as a medium of wave propagation, is characterized by extreme manifestation of dispersion, that is, its weak manifestation inside longitudinal and transverse waves, and a degenerate case resulting in a great difference in the velocities of both types of waves.

It is also known that this difference increases with distance. In view of this fact, let us analyze the solution to equation (5) as expansion by a small parameter ε: $u = \varepsilon u_1 + \varepsilon^2 u_2 + \varepsilon^3 u_3 + \ldots$ For the terms with ε^2, equation (5) for the second harmonic u_2 takes the form

$$\frac{\partial u_2}{\partial t} + Lu_2 = -u_1 \frac{\partial u_1}{\partial x}, \qquad u_2(x,0) = 0. \tag{6}$$

Its solution has the form [6]:

$$u_2 = -2i\,ka_1^2 \frac{\sin(\Delta\omega t/2)}{\Delta\omega} \exp\Big[i\Big(2kx - \frac{\omega_{2k} + 2\omega_k}{2} t\Big)\Big] + \text{c.c.} \tag{7}$$

Here a_1 is the amplitude of displacement of the medium particles caused by the base wave, and c.c. is the term that is complex conjugate to the first one. It follows from equation (1) that with a decrease in the deviation, the level of the second harmonic increases. In the case of dispersionless waves (when $\omega_k = ck$), we have a maximum value. For this case, expression (1) takes the form

$$u_2(x,t) = -i\,ka_1^2 t \exp\big[i(2kx - \omega_{2k}t)\big] + \text{c.c.} \tag{8}$$

This expression shows that the level of the second harmonic grows proportional to the wave travel time, so that the linear approximation with an arbitrarily small ε becomes incorrect. The accumulation of the nonlinear effects in space is determined by the dependence of the amplitude of the second harmonic on the distance described by the ratio [7]:

$$a_2 = \frac{K_C r\omega^2 a_1^2}{8c_p^2}. \tag{9}$$

Here r is the wave travel length, $K_C \approx \rho c_p \dfrac{\Delta c_p}{\Delta p}$ is the nonlinearity coefficient of the medium in which ρ is density, Δp is the pressure variation, and c_p is the compression wave velocity. The value of this coefficient according to some authors is $\approx 10^3$.

4. The role of 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 [8] and the multidisciplinary approach by A.S. Alekseev [9] consider the processes of development of a system of cracks resulting from the growth of the volume density of microcracks in the destruction zone. Taking this into account, in [9] it was proposed to use a spatial function $\theta(x,y,z,t)$, with whose help 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 the medium can provide more detailed data about the structure of medium zones with time varying-fracturing (Figure 6). It was proved for the recorded wave field in the far zone [7] that the dynamic characteristics of the wave field are most

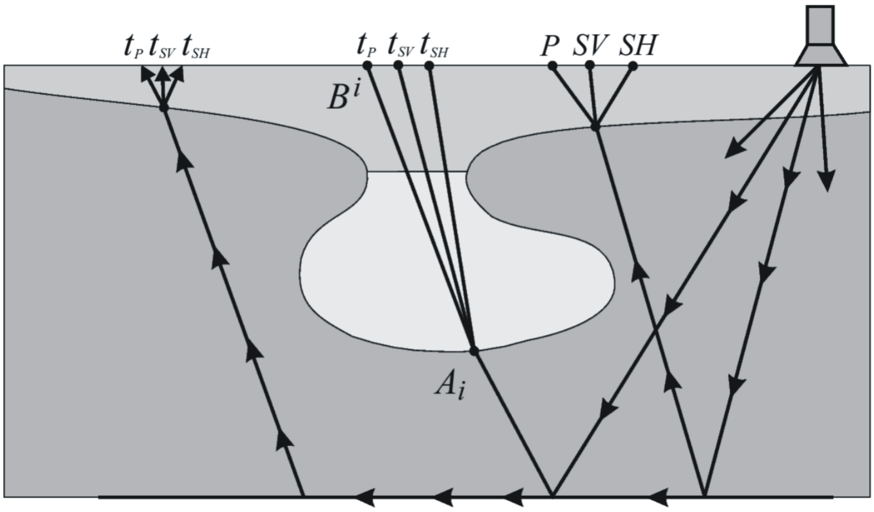


Figure 6. Scheme for the profile of vibroseismic observations

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 nonlinearity parameters of the wave field, which causes the appearance of high harmonics (enriching the initial sounding monochromatic oscillations), should be taken into account. With allowance for this, it is important to relate the characteristics of the wave field nonlinearity and the parameters of medium fracturing.

In [8], such a dependence was obtained for a model of fracturing occurring in a homogeneous and isotropic medium with the elasticity moduli K_1, μ_1 and the density ρ_1. Uniformly scattered and chaotically oriented voids of the 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 minimum value $\alpha_{\min}$ and maximum 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 simulated medium is much greater than the linear dimensions of the largest voids. The following relations for the effective elasticity moduli of a medium with spheroidal voids are obtained:

$$K_{(1)} \approx K_0\left[1 - \varphi_0 a \frac{K_0^2}{p_0 K_1} f(\alpha_0) u_{ll}\right], \quad \mu_{(1)} \approx \mu_0\left[1 - \varphi_0 b \frac{K_0 \mu_0}{p_0 \mu_1} f(\alpha_0) u_{ll}\right].$$

Here $K_0 \approx K_1(1 + \varphi_0 a F)^{-1}$, $\mu_0 \approx \mu_1(1 + \varphi_0 b F)^{-1}$, $b = \frac{8(1-\nu_1)(5-\nu_1)}{15\pi(2-\nu_1)}$,

$f(\alpha_0) = \dfrac{\varphi(\alpha)}{\varphi_0}$, $\varphi_0 = \displaystyle\int_{\alpha_0}^{\alpha_{\max}} \varphi(\alpha)\, d\alpha$ is the initial value of the medium fracture porosity, $F = \displaystyle\int_{\alpha_0}^{\alpha_{\max}} \frac{f(\alpha)}{\alpha}\, d\alpha$, 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.

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

$$\rho_0 \frac{\partial^2 u_x}{\partial t^2} - M_0 \frac{\partial^2 u_x}{\partial x^2} = B \frac{\partial u_x}{\partial x} \frac{\partial^2 u_x}{\partial x^2}. \tag{10}$$

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

$$u_x = U_x \sin(\omega t \pm k_P x) - \left(\frac{U_x}{2}\right)^2 \frac{B}{M_0} k_P^2 x \cos 2(\omega t \pm k_P x), \tag{11}$$

where $k_P = \omega / c_P$, $B = -3\varphi_0 \frac{k_0}{p_0}\left(a\frac{k_0^2}{k_1} + \frac{4}{3} b \frac{\mu_0^2}{\mu_1}\right) f(\alpha_0)$, $M_0 = k_0 + \frac{4}{3}\mu_0$.

It follows from (11) 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 proportionally increases with x. This phenomenon was noted earlier as accumulating nonlinearity in a nonlinearly elastic medium. With allowance for (11), the coefficient of nonlinearity of the monochromatic wave shape, determined by the ratio between the amplitudes of the base and the second harmonics, is as follows:

$$\frac{u_2}{u_1} = \frac{1}{8} \frac{U_x B k_P^2 x}{M_0}. \tag{12}$$

One can see that this expression is further refinement of (9), obtained for the case of propagation of seismic oscillations in homogeneous media with energy dissipation and wave dispersion.

Equation (12) relates the parameters of wave field nonlinearity in the destruction source zone and the medium fracturing determined by the parameter B, which depends on the size 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 as evolution of 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. The effectiveness of using these parameters is illustrated below for the geodynamic processes occurring in the Earth's crust during the lunar-solar tides.

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. Spectrograms of the mixture of useful monochromatic signals and noise confirm the possibility of detection of the 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 7a and 7b, respectively. It follows from the spectrograms that the ratio between the maxima m of the both signals is $243.4/501.4 = 0.48$.

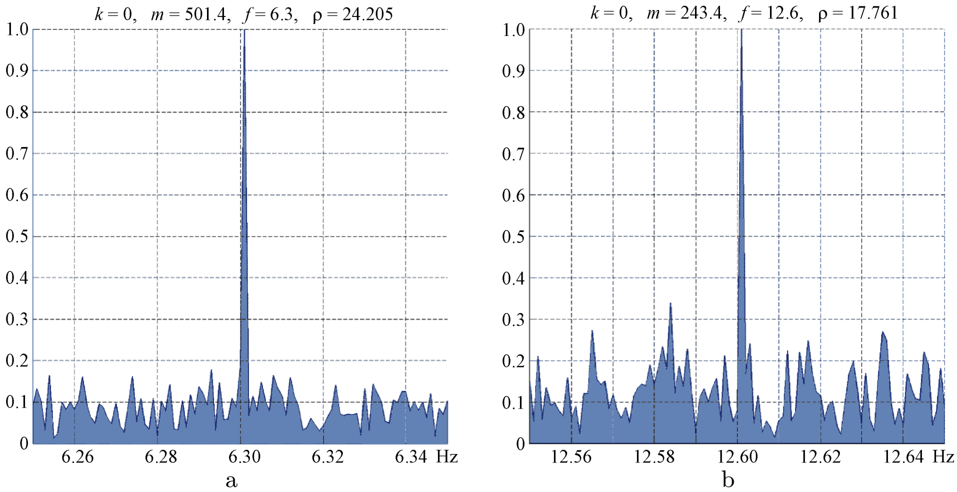


Figure 7. Spectrograms of the base and the second harmonics at the distance of 355 km

The amplitude ratios of the second and the base harmonics of oscillations were recorded during the Earth's soundings with the help of periodically repeating (with a period of 3 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 [3]. This paper investigates the possibilities of selecting daily and half-daily periodicity in variations of the seismic field parameters for the lunar-solar tides. The time series as estimates of 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 recording seismic signals. For this, the quadrature algorithm was used to measure the amplitudes of stable oscillations [2].

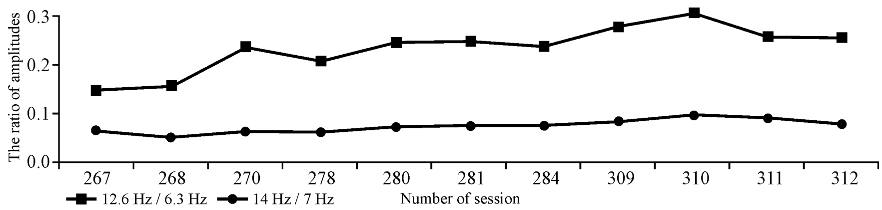


Figure 8. The ratio between the second and the base harmonics in the source

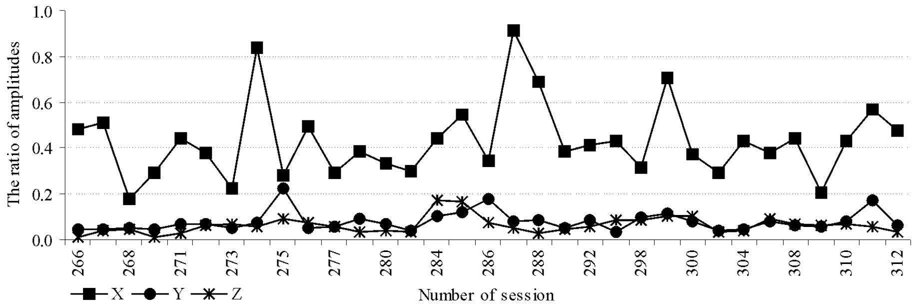


Figure 9. The ration between the second (12.6 HZ) and the base (6.3 Hz) harmonics at the 5th gauge

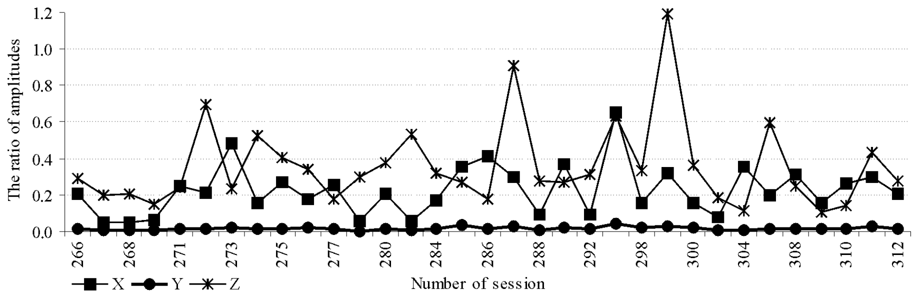


Figure 10. The ration between the second (14 HZ) and the base (7 Hz) harmonics at the 5th gauge

Here, recording with the components X, Y, Z was used. According to the above, the corresponding results of data processing are stages illustrated in Figures 8–10. In the figures, the abscissa axis represents the session number, and the ordinate axis shows values of the ratios between the harmonics.

As a comment to the diagrams presented, it should be noted that the plots in Figure 8 reflect the ratios between the second harmonic of radiated oscillations and the base one at frequencies of 6.3 and 7.0 Hz. These data correspond to the parameters of the radiated seismic field in immediate proximity to the source (at a distance of 30 m). It is seen that the greatest nonlinear effect 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 %.

Figures 9 and 10 show similar ratios obtained at a 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 diagrams obtained that the greatest values of the ratios are with the components X and Z. Their values at different sounding frequencies are different. Thus, at a frequency of 6.3 Hz, the ratios of harmonics are within 20–90 % with the component X and about 10 % with the component Z. At a frequency of 7.0 Hz, the ratios are 5–40 % and 20–90 %, respectively. The external noise affects fast fluctuations of the ratios obtained (from session to session). If these data are compared to those observed near the source, it becomes obvious that the ratios of harmonics at the distance considered are, on average, higher. In particular, we have 45 % against 7.5 % at 7.0 Hz and 50 % against 25 % at 6.3 Hz. A real difference between these values is even higher. This is due to additional attenuation in the medium of high-frequency harmonics appearing at the stage of radiation of seismic oscillations. Changes in the initial ratios between the second and base harmonics a_{02}/a_{01} observed in the destruction source zone, depending on a distance, vary according to the following law:

$$\frac{a_{f_2}(r)}{a_{f_1}(r)} = \frac{a_{02}}{a_{01}} \exp\bigl[(\alpha_2 - \alpha_1)(r - r_0)\bigr], \tag{13}$$

where $\alpha_{1,2} \approx 2.5 \cdot 10^{-4} f_{1,2}$ km^{-1} is the coefficient of medium absorption due to non-ideal elasticity, and r_0 is a "source-receiver" distance near the source zone. In view of the ratio of harmonics near the source (see Figure 1), its value at a distance of 355 km is associated with a sounding frequency of 6.3 Hz. With allowance for (1), we have $\frac{a_{12.6}(355)}{a_{6.3}(355)} \approx 0.57\frac{a_{02}}{a_{01}}$. This means that the share of the second harmonic in the ratio between the second and the base harmonics at a distance of 355 km decreases by a factor of 1.75. Obviously, the observed increase of the nonlinear effect should be related to the contribution of the nonlinear processes of propagation of seismic oscillations in the medium. It follows from this assumption that in the multidaily dynamics of the nonlinear process, its connection with the deformation processes in the medium due to the lunar-solar tides should manifest itself. It is known that the deformation processes are characterized by daily and 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. The results of this selection for the observation series corresponding to the ratios between the amplitudes of the second and the first (base) harmonics with sounding frequencies of 6.3 and 7.0 Hz are presented in Figures 11a and 11b, respectively. Both diagrams are for the observation series corresponding to the component Z. It follows from these diagrams that daily periodicity is confidently distinguished

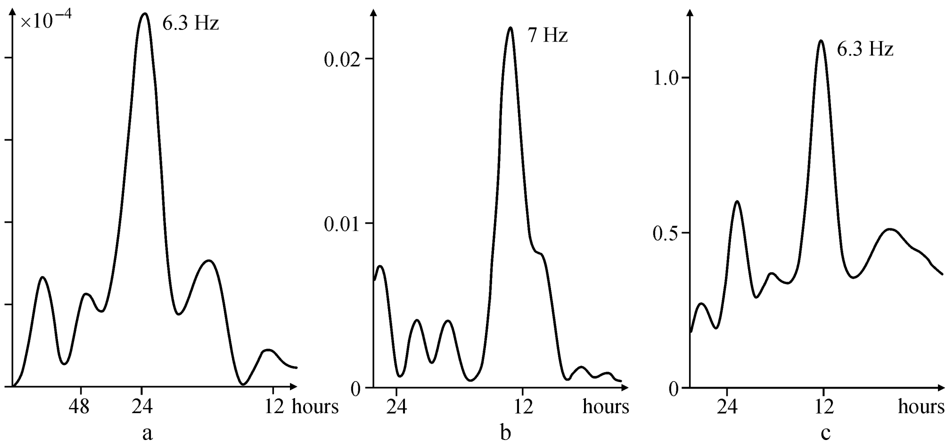


Figure 11

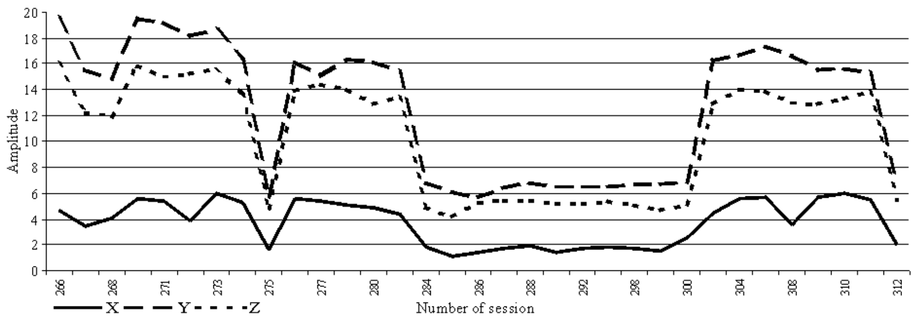


Figure 12. Levels of radiated signals

within the time series $\frac{a_{12.6}(355)}{a_{6.3}(355)}$, and half-daily periodicity — within the series $\frac{a_{14}(355)}{a_{7.0}(355)}$. Therefore, different sensitivity of the sounding frequencies to the daily and the half-daily periodicity should be taken into account at the stage of selecting the parameters of sounding.

An advantage of the monitoring method proposed is its invariance with respect to fluctuations of the amplitude of radiated oscillations 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 the amplitudes of the secondary and the base waves at a distance of 355 km. The 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 sharp decreases in the oscillation levels caused by an “artificial” decrease in the amplitude of the perturbation force of the original source-vibrator CV-100. Despite this fact, the stability of the process of detecting the half-daily and the daily periodicities at a remote recording point due to the terrestrial tides was 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: the fluctuations of the radiation oscillation levels bring about the corresponding fluctuations of the signal levels at a receiving point. At the same time, when introducing proper corrections into abrupt decreases in the amplitudes, it appears possible to detect the daily and the half-daily periodicities in the graphs of the amplitudes of the base (primary) harmonics (see Figure 11c).

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 the amplitudes of the second and the base harmonics of seismic oscillations at the background of noise and 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 the medium due to geodynamic processes are proved. This is especially important for the problems of long-term tracing of the processes of preparation of disasters in seismic-prone zones.

References

[1] Khairetdinov M.S. The nonlinear wave effects in vibroseismics // NCC Bulletin, Series Math. Model. in Geophysics. — Novosibirsk: NCC Publisher, 2003. — Iss. 8. — P. 59–68.

[2] Khairetdinov M.S. Methods of distributed processing of vibroseismic signals // Proc. Intern. Conf. “Information systems and technology”. Novosibirsk State Technical University, Russia. — Novosibirsk, 2004. — Vol. 3. — P. 607–612.

[3] Glinskii B.M., Kovalevskii V.V., Khairetdinov M.S. Vibroseismic monitoring of earthquake prone areas // Volcanology and Seismology. — 2000. — Vol. 21. — P. 723–730.

[4] Antennas / Ed. by L.D. Bakhrakh. — Moscow: Sov. Radio, 1979.

[5] Tikhonov V.I. Optimal Signal Reception. — Moscow: Radio and Communication, 1983.

[6] Breckovskick L.M., Goncharov W.W. Introduction to a Mechanics of the Continuous Medium. — Moscow: Nauka, 1982.

[7] Zarembo L.K., Krasilnikov W.A. Introduction to Nonlinear Acoustics. — Moscow: Nauka, 1966.

[8] Zhurkov S.N. Kinetic concept of strength of solid bodies // Vestnik Akad. Nauk SSSR. — 1968. — No. 3. — P. 46–52.

[9] Alekseev A.S., Belonosov A.S., Petrenko V.E. Determination of an integral earthquake precursor with the use of a multidisciplinary model and active vibroseismic monitoring // Proc. ICM&MG SB RAS, Ser. Math. Modeling in Geophysics. — Novosibirsk, 1998. — No. 7. — P. 3–36.

[10] Verbitsky T.Z. Peculiarities of elastic wave propagation in nonlinearly elastic porous media // Problems of Nonlinear Seismics. — Moscow: Nauka, 1987. — P. 94–103.