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Nonlinear Phenomena in Seismic Surveying Using Periodic Vibrosignals

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It is experimentally substantiated that nonlinear effects develop significantly during propagation of extended periodic signals from seismic vibrosources at distances where seismic deformations are traditionally considered to be small. The effects are studied quantitatively for generation of multiple harmonics of sinusoidal seismic signals, combinations of interacting signals with formation of waves having sum-difference frequencies, and self-demodulation of amplitude-modulated seismic signals. The experimental results obtained indicate a high physical nonlinearity of real media.

Study of nonlinear phenomena in seismic surveying has always received little attention. It has been considered that all nonlinear effects are concentrated in a zone near the seismic sources, whereas outside this zone at distances on the order of a few wavelengths, the propagation of seismic oscillations follow the laws of linear elasticity theory to an accuracy adequate for practical applications. Such an assumption, generally speaking, has been justified. The linear model of seismic phenomena is distinguished by an adequate simplicity and has permitted creation of the powerful methodology of modern seismic exploration, which has successfully solved many practical problems.

An important distinguishing feature of classical seismic exploration and seismology has been the use of impulse sources of seismic waves. The oscillations of such sources have a wide spectrum. The continuous spectrum of harmonics, characteristic for impulse signals, makes it difficult to observe nonlinear phenomena as a result of mixing of the arising multiple and sum-difference waves from all components of the continuous spectrum. Such phenomena are extremely convenient to observe using harmonic signals.

The appearance of seismic vibrators practical for scientific investigations raised the possibilities of experimental seismic surveying to a new technical level [1]. The basic advantages of the seismic vibrator are the repeatability of the action, the ability to regulate the power and the continuous signals over a wide frequency band, which permits high-precision observations and tracing the evolution of individual harmonic components, including during study of nonlinear phenomena. During nonlinear processes each period of a sinusoidal wave is distorted, as a result of which it is possible to accumulate these distortions at any desired extent of occurrence, by regulating the signal/noise and

separating as desired the weakest effects. Such a possibility was excluded when working with impulse sources.

Nonlinear phenomena during propagation of elastic waves in solid bodies have been investigated in detail in nonlinear acoustics. A review of the basic experimental results can be found in [2, 3]. Study of nonlinear seismic phenomena has thus far been the subject of only individual theoretical and practical works, and there is no systematic experimental study of them over a wide range of frequencies and distances.

M. A. Grinfel'd theoretically investigated the questions of propagation of seismic fronts from weak ruptures in a nonlinear elastic medium and described a series of effects, which could be ascribed to nonlinearity of the process [4]. He showed that in real geological media it can be expected that the parameters of physical nonlinearity will have a very great significance.

There exists a series of direct experimental indications of high physical nonlinearity for rocks in samples and in the natural setting. In particular [5], in which the third-order constant of elasticity was directly measured for a series of crystalline rocks, shows that a typical value for this parameter of nonlinearity for them is 10^4 . These and even greater values are obtained from experiments that measured under natural conditions the dependence of the propagation velocity of seismic waves on the external stresses applied to the medium, and which are adequately referenced to experiments [6, 7]. It is known that the degree of dependence of propagation velocity of seismic waves on the external pressure is a direct quantitative criterion of physical nonlinearity for rocks [1, 8]. The results of [6, 7] show that the medium in the natural state is more nonlinear than in samples.

Measurement of dependencies of the $v(P)$ type, where v is velocity and P is pressure, is an

example of the measurement of static nonlinearity. The linearity parameters thus obtained are on the order of 10^4 or more and are very high. It is adequate to say that in nonlinear acoustics of a solid body the values of the nonlinearity parameters used do not exceed 10^1 to 10^2 . From this it is clear that in seismic surveying perceptible development of nonlinear phenomena can be expected even at small amplitudes of the propagating waves.

Dynamic nonlinearity is expressed in the interaction of seismic waves and the distortions of the shape of similar seismic signals. Some results from the study of dynamic nonlinearity in real media and samples are described in [1, 9-11]. Summary information on the works completed and the basic directions of these investigations is contained in [12, 13]. In all these works is the conclusion that there is a significant influence of nonlinear effects on the propagation of seismic waves. Measurements of the nonlinearity parameters of the medium, done independently in some of the enumerated works studying the appearance of dynamic nonlinearity, generally give values lower than those noted above. These values are on the order of 10^3 .

In this work an attempt is made to systematically experimentally study the formation of nonlinear effects during propagation of some characteristic types of periodic seismic vibro signals over a wide range of frequencies and distances between the source and receiver. The work was done over several years in the Gomel region.

The upper part of the section in the region where the work was done is composed of loose sand deposits, below which are salt deposits and high-velocity units of crystalline basement. The section is characterized by complex dislocations.

A domestic mobile vibrator, SV 10/100 made by the Gomel SKB, was used to produce the oscillations. A vibrator of this type is capable of creating seismic oscillations in the range from about 10 to 100 Hz and with a force applied to the ground of from about 1 to 10 Ts. A powerful 50-ton stationary vibrator was also used, the construction of which provides predominant excitation of body waves.

The seismic wave field was recorded on the surface of the medium at various distances from the source by the 24-channel system of the digital seismic station "Progress-2." Seismographs SM-3, SV-5Ts, SV-10Ts, and SV-20Ts were used.

During digital recording the digitizing interval was 2 ms. Recorded samples of the wave field, 16 s in length, were spectrally reduced on an EVM YeS-1033 computer. Calculation of the spectra used a BPF algorithm. The 16-s records provided $213 = 8192$ points in the analyzed time series and the corresponding frequency is equal to $1/(8192 \times 0.002)$, or about 0.06 Hz. The Nyquist frequency in this case is $1/(2 \times 0.002) = 250$ Hz.

The methodology used in the experimental work was generally the following. Before

conducting a routine experiment a sample of the microseismic noise was recorded; it was verified that it did not contain a determinative harmonic component that was independent of the conditions of the experiment. Then the experiment was done: samples of the established interference wave field were recorded at a series of points located at distances from several meters to 4 to 5 km from the source. Thus, the possibility existed to trace in detail the spatial evolution of the vibroseismic field from the zone near the emitter, where the recorded signal can be considered the "input" to the medium, to distances that many fold exceed the length of the emitted wave, where the seismic deformation is low.

Three possible methods were used for regulating the distance of a reception point from the vibrator: removing the vibrator itself, removing the reception cable, and laying out long lines with the reception cable. The identity of the repetitive actions of the vibrator were verified. Crossed control, alternation of various variants of the observational scheme, and multiple repetitions of the experiments under various conditions excluded the possibility of introducing false and distorted effects as a result of change in the conditions of setting up the sources or receivers. In addition, the presence of 24 independent recording channels in the reception cable, located 10 m apart, also gave adequate control information.

After each routine experiment a second sample of the seismic noise was recorded, the characteristics of which could have changed during the observations.

PROPAGATION OF THE HARMONIC VIBRO SIGNAL

Figure 1 shows a typical example of an observation at various distances from the vibrosource of the spectra of the 20-Hz signal emitted by the SV 10/100 vibrator. The vibrator was working at maximum power. The spectrum of the microseismic noise is also shown. The spectra in Fig. 1 and in all subsequent figures are given in relative units. In the upper right corner of the figure two periods of the oscillogram of the signal are shown, corresponding to the spectra shown (the amplitudes are also in arbitrary units).

The following picture of the signal propagation is observed. In the zone near the source (a distance of about 100 m), as a result of either nonlinearity of the source itself or distortion in the zone of strong deformation under the plate of the vibrator, a third harmonic arises, which is very weak compared with the amplitude (the ratio $A_3/A_1 = -40$ dB, where A_3 is the spectral amplitude of the third harmonic and A_1 is the spectral amplitude of the basic harmonic). In the temporal region no visible distortion of the sine wave was observed (Fig. 1a). Further propagation of the signal in the medium has a clearly nonlinear character: on the background of a decrease in the total amplitude of the basic signal there

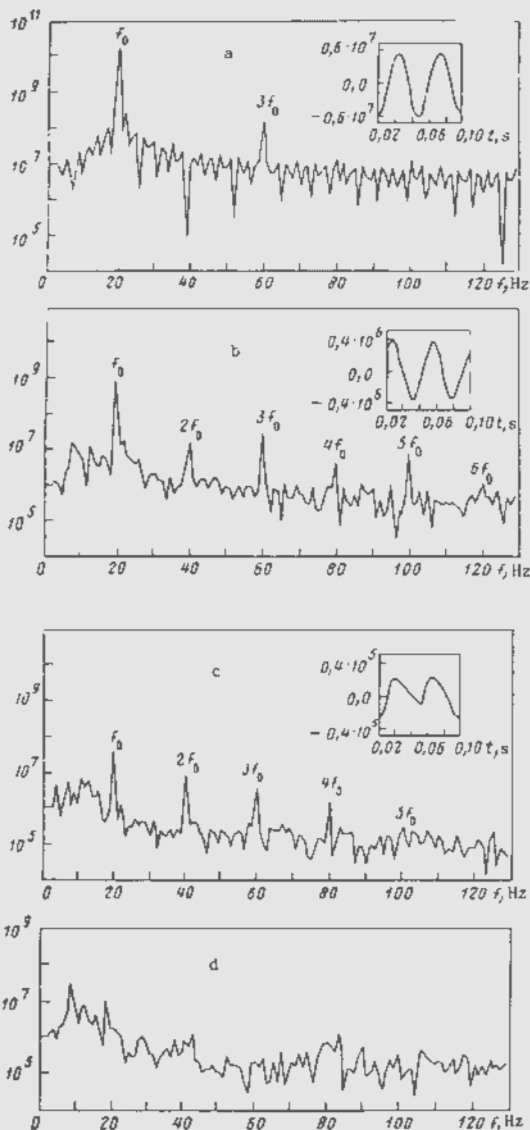


Fig. 1. Amplitudinal spectra for the field of a 20-Hz vibrosignal at various distances from the vibrator: a is 100, b is 500, c is 1700 m and d is the spectrum of the microseismic noise. The ratio of spectral amplitudes of multiple harmonics to the amplitude of the basic harmonic: a is $A_2/A_1 = -64$ dB, $A_3/A_1 = -40$ dB; b is $A_2/A_1 = -34$ dB, $A_3/A_1 = -30$ dB, $A_4/A_1 = -14$ dB; c is $A_3/A_1 = -20$ dB.

arise (and grow in relative amplitude) repeated harmonics up to the sixth, inclusive, and there is observed a gradual distortion of the signal in the temporal region (Fig. 1b, c). Figure 1c is notable because the shape of the signal takes on a nearly sawtoothed form and the leading front

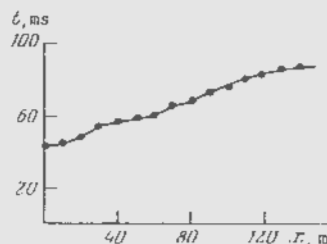


Fig. 2. Experimental traveltime curves of one of the phases of the nonlinearly distorted signal at a distance of about 1700 m from the vibrator.

of the wave "avalanches," which corresponds practically to the maximum nonlinear distortion. The distribution of harmonics with amplitude has a smooth decreasing character and quantitatively corresponds to the spectral composition of sawtooth elastic signals, recorded in the fields of powerful acoustic emitters and described in the literature of nonlinear acoustics (see for example [3, p. 582, Fig. 16]).

We also observed the 20-Hz signal at a distance of 5000 m from the vibrator. These observations show that nonlinear distortions even at this distance still exist, although they are reduced: the second and third harmonics were observed.

The noise spectrum given in Fig. 1d shows no predominant harmonic in the microseismic field, with the exception of strong noise in the LF-region around 10 to 15 Hz.

Under conditions of multiple-ray propagation it is important to establish the type of waves and the parts of the medium that are most responsible for the nonlinear effects, recorded in the total interference picture at the surface. We analyzed the wave picture at many points of the recording on the 24 recording channels with the goal of correlating the phases, determining the apparent velocities and the exit angles of the recorded oscillations.

Figure 2 shows an example of a travel-time curve constructed using the values for one of the phases of a nonlinearly distorted signal, corresponding to Fig. 1c, in 15 adjacent channels. The phases were reliably identified.

The value of the apparent velocity obtained from this travel-time curve is $140/0.044$, or about 3200 m/s. Such a high velocity cannot belong to a surface wave: the range of velocity change for surface waves in the region of the work does not exceed 500 to 600 m/s. Therefore, it is reasonable to propose that the nonlinear distortions and multiple harmonics recorded at this distance arise in body waves. Its exit angle can be estimated using the obtained value of the apparent velocity and taking the average velocity of longitudinal waves in the near surface unit to be about 2000 m/s. Then we obtain

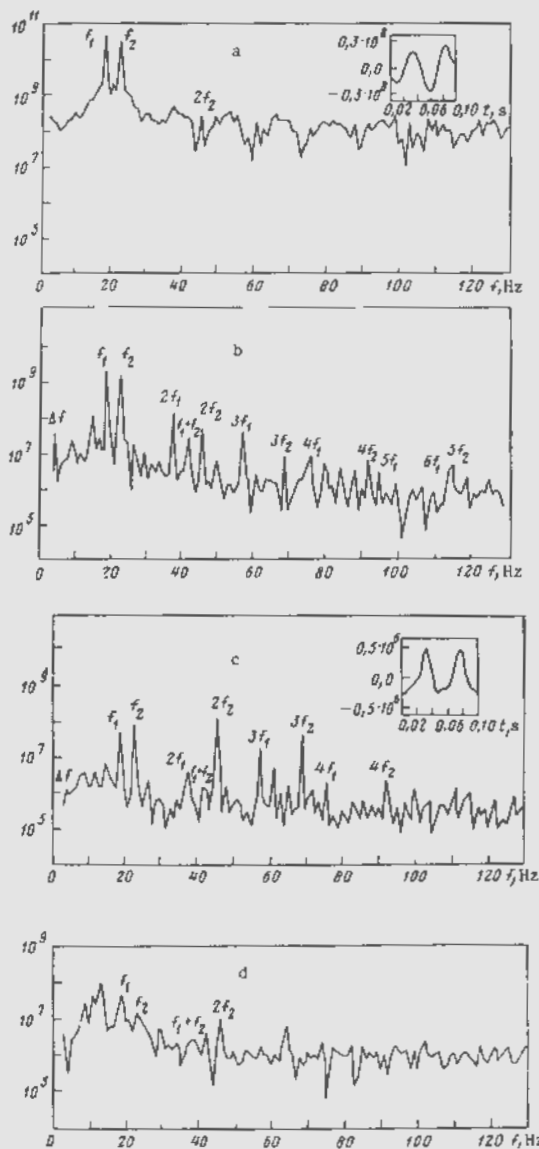


Fig. 3. Amplitudinal spectra of the vibro-signal containing the sum of the frequencies 19 and 23 Hz, at different distances from the sources: a is 100, b is 440, c is 1000 and d is 5000 m.

$$\sin \theta \sim \frac{c}{c_k} \sim \frac{2000}{3000} = 0.625 \text{ and } \theta \sim 40^\circ$$

(θ is the exit angle relative to the vertical).

PROPAGATION OF A SIGNAL CONTAINING TWO SUPERPOSED FREQUENCIES

Another series of experiments studied the propagation of signals composed of the sum of

two sinusoidal waves of different frequencies. The difference in frequencies was regulated and varied in the experiment from 4 to 40 Hz. The signals were produced by two SV 10/1000 vibrators, working at maximum power.

During propagation of such dual-frequency oscillations a greater nonlinear effect is observed in comparison to the case of a single sinusoidal signal. Here, in addition to the effects of doubling, trebling, etc., of the frequencies of each individual sinusoidal component, are the effects of their crossed interactions, the simplest of which is the formation of sum and difference frequencies, and effects of higher order, where there arise combined frequencies described in the general case by the formula $m f_1 \pm n f_2$, where f_1 and f_2 are the frequencies of each component of the dual-frequency signal and m and n are the natural numbers. However, the higher the order of the coefficients m and n , the lower the effectiveness of the generation of the corresponding combined harmonic.

The experimental results for the difference in frequencies of the produced frequencies $\Delta f = |f_1 - f_2| = 4$ Hz is shown in Fig. 3. The frequency f_1 in this case is equal to 19 Hz and f_2 is 23 Hz.

Near the vibrators (a distance of 100 m) the effects of interactions are insignificant, and the signal in the temporal region is practically undistorted and appears as the ordinary dual frequency beat (Fig. 3a). Already at a distance of 440 m (Fig. 3b) there is a noticeable series of multiple and combination harmonics, forming a regular "comb" of spectral peaks at 4-Hz intervals, which corresponds to the above-given scheme of interactions for various values of the coefficients m and n (in Fig. 3b only the peaks corresponding to multiple, sum and difference harmonics are noted: the remaining combined harmonics are not marked and they are somewhat weaker in amplitude, but clearly separated).

At a distance of 1000 m the second and third multiple harmonics are even more amplified in relative amplitude (Fig. 3c). The harmonic $2f_2$ exceeds in amplitude the harmonics of the basic frequencies. Such a phenomenon is possible at several points of observation under the conditions of multiray propagation when, because of interference phenomena, the field of harmonic signals in space starts to "flicker," and a "fading" is observed at one frequency and stimulation at others. It is notable that the relative growth of amplitude for all multiple and combined harmonics at a distance of 1000 m occurs on a background of decrease in the total amplitude of the recorded seismic signal of two orders of magnitude relative to the point of excitation. Nonlinear distortions of the signal are directly observed on the oscillogram (Fig. 3c).

Figure 3d shows the spectrum of the signal recorded at a distance of 5000 m. The effects of nonlinear interaction are still preserved, even though at this distance the waves of the basic frequencies are lower in amplitude than the level

of microseismic noise and are not seen on the oscillograms. Their upper amplitude can be estimated from the average observed amplitude of the microseisms u_0 , which in the region of the work

is approximately 10 to 100 micron. The wavelength of the signal λ at frequencies of 19 to 23 Hz (if we start with the average velocity of propagation of longitudinal waves in the units covering the crystalline basement, and in the basement itself, being about 4000 m/s) can be set equal to 200 m. Thus, the range of Mach numbers $M = 2\pi u_0/\lambda$ for the seismic signal from the vibrator at the indicated distance is about 3×10^{-10} to 3×10^{-9} . Even at these small values nonlinear effects still appear. The cause of this can be only the very high physical nonlinearity of the rocks in the path of the propagated signal.

We conducted experiments with other values for the difference in emitted frequencies Δf . A regularity was recognized: signals with similar frequencies, differing by 4 to 6 Hz, interact the most effectively. No interaction was noted for signals differing 20 to 40 Hz in frequency. Apparently, such a phenomenon reflects a general property of the interactions of the seismic fields: signals with comparable frequencies interact. One of the cases of such interaction, synchronization of close spectral lines, is described in [14].

PROPAGATION OF AN AMPLITUDE-MODULATED SIGNAL

The propagation of an AM signal is of great interest from the point of view of studying nonlinear effects. In the case of sinusoidal modulation such signals have three frequencies, consisting of the carrier frequency and two side frequencies: $f_0 - \Omega$ and $f_0 + \Omega$, where Ω is the modulation frequency. A characteristic effect accompanying the propagation of an AM signal in a nonlinear medium is its self-rectification, which is separation of the diffraction frequency in a nonlinear medium.

To produce the AM signal we used the powerful low-frequency 50-ton vibrator. The carrier frequency was 19 Hz and the modulation frequency was 4 Hz. In this experiment the recording was done by a 30-s window with a 4-ms digitizing interval.

Figure 4a shows the amplitude spectra of the studied signal at a distance of 70 m from the vibrator. The intense harmonics f_0 , $f_0 - \Omega$, and $f_0 + \Omega$ are recognized, corresponding to the tri-frequency spectrum of the initial AM signal. Other harmonics are present but they are 30 to 40 dB weaker than the initial harmonics. The oscillograms show the initial signal with a frequency of 19 Hz and variable amplitude.

Figure 4b shows the spectrum of the signal at a distance of 1600 m from the vibrator. The frequency composition of the field has changed.

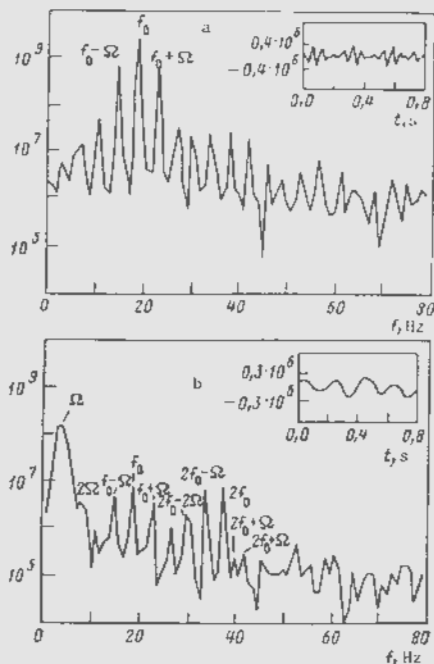


Fig. 4. Amplitudinal spectra of the field of an amplitude-modulated signal with a carrier frequency of 19 Hz and a modulation frequency of 4 Hz at various distances from the vibrator: a is 70 and b is 1600 m.

A powerful wide-band rectification low-frequency signal predominates with a maximum at the modulation frequency of 4 Hz, which is 25 to 30 dB greater than the level of all other spectral components. Components at frequencies of 2Ω , $2f_0$, $2f_0 - 2\Omega$, $2f_0 - \Omega$, are reliably separated, and which are about equal in amplitude to the components at the initial frequencies f_0 , $f_0 - \Omega$ and $f_0 + \Omega$. Weak peaks are separated at frequencies of $2f_0 + \Omega$ and $2f_0 + 2\Omega$. The compositions of the indicated harmonics, which have significantly increased in relative amplitude during propagation from the vibrator, precisely correspond to the composition of the spectrum of the AM oscillation, having passed through the quadratic detector [15]. The LF signal of the diffraction is directly visible on the oscillogram (Fig. 4b). Analysis of the traveltime curve has shown that this signal is a body wave with an exit angle relative to the vertical of about 40° , as is the case for the harmonic signal at this distance.

Similar results were obtained when using a frequency modulation of 2 Hz.

DEPENDENCE ON POWER

The appearance of nonlinear effects, even when the physical nonlinearity of the medium is

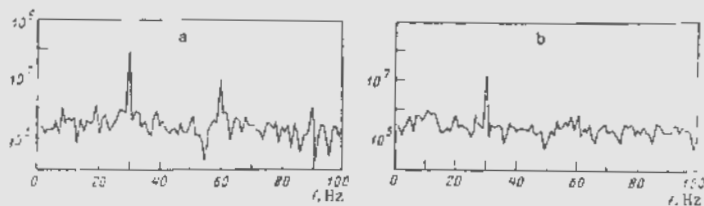


Fig. 5. Amplitudinal spectra of the field of 30-Hz harmonic vibrosignal at a distance of 750 m from the vibrator for different power levels of the excitation: a is the maximum and b is the minimum.

very strongly expressed, should depend on the amplitude of the waves excited by the vibrator. But in the final analysis these effects should not appear when the amplitude tends toward zero.

When conducting the experiments they were repeated at various force levels applied to the emitting element of the vibrator. This served as a source of supplemental control information, because a smooth decrease in the nonlinear effects with reduction in amplitude at the source would indicate the correctness of the interpretation given to the observed nonlinear phenomena.

Figure 5 shows two spectra recorded at a distance of 750 m from the SV 10/100 vibrator. A monochromatic 30 Hz signal was studied. Figure 5a is for the case where this signal is excited at maximum power, which is about 10 Ts, whereas Fig. 5b is for excitation at the minimum power of the vibrator, about 10 times less. It is seen that in the first case intense multiple harmonics are excited, while in the second case they are absent. The noise level between the spectral peaks in both cases is the same, which indicates that this noise is only from microseismic activity.

Concluding the discussion of the experimental data, we note that the intense nonlinear effects observed in the vibroseismic fields can be explained by the effective parameters of nonlinearity in the medium being in the 10^3 to 10^4 range along the propagation paths.

CONTROL AND UNCERTAINTIES

When observing such refined phenomena as nonlinearity, one of the central factors is the multiple control and the exclusion of all extraneous sources of introducing nonlinearity. In the schemes used for observations and recording the following sources of nonlinear distortion are possible: the vibrator, including the contact zone, the medium, the geophones, the electrical circuit of the seismic recording station, and the combination of procedures for quantifying the signals arriving at the station. Of all these sources of nonlinearity only one is important, the medium in which the seismic waves are

propagated, and it should be possible to exclude all of the remaining possibilities.

Such control was achieved in the following manner. The nonlinearity of the vibrator and the contact zone was always controlled by seismographs emplaced in the direct vicinity of the vibrator. In this manner all harmonics emitted by the system source-ground were considered and the subsequent calculation of the relative growth of the harmonics was in effect done from this "starting" level. For investigating the growth of nonlinear effects in the far zone of the source the only cases selected were those for which the vibrator worked adequately "cleanly" and the relative level of multiple harmonics near it did not exceed -35 to -40 dB. Cases of "poor" working of the source were simply rejected.

Nonlinearity of the geophones is negligible, and it is difficult to imagine that it introduced the large nonlinear distortions recorded at distances of 1 to 2 km from the vibrator, where the displacements have very small amplitudes, while at the same time near the sources the same geophones showed a hugely reduced level of distortions.

The electrical circuit of the seismic station was controlled by recording signals from a generator and subsequent spectral analysis of them. This control showed negligible nonlinear distortions introduced by the stations, which did not exceed the instrument specifications of 0.1%.

The procedure for quantifying the signal in time and level was separately modeled over a wide range of frequencies and shapes of the signal using a computer. The process of filling the 14-discharge grid of the seismic station "Progress 2" was imitated. The effects that could occur during incomplete filling of the discharge grid and the distortions resulting from this were modeled. Effects, even approaching within an order of magnitude of those recorded in the experiment, were not found.

The combination of control procedures used permits adequate reliability in concluding that nonlinear seismic phenomena, occurring during the propagation of a signal in a real medium, were recorded. The regular character of these distortions is also convincing, as is the completeness of their correspondence with theoretical premises.

CONCLUSIONS

The completed experimental works have demonstrated the intense development and the possibility of reliably recording nonlinear seismic phenomena when studying long-period signals and the applications of ordinary seismic survey vibrators and high-powered vibrators as sources.

On the basis of the results obtained, an approximate picture can be constructed of the formation of nonlinear effects in the seismic field. In the zone adjacent to the vibrator, in the region of strong deformations of the medium, and also in the contact zone of the plate with the ground, nonlinear distortions occur, which, however, do not exceed -38 to -40 dB in amplitude relative to the harmonic of the basic tone. Then, starting at a distance of 100 to 200 m from the vibrator in the seismic frequency range (in our experiments this is 20 to 70 Hz), the formation of nonlinear effects continues in agreement with the law of traveling waves, known in nonlinear acoustics and optics. The nonlinear distortions accumulate with distance and can attain bounding values that are characteristic for nearly sawtooth waves. The spectral composition of the signal at distances of 2 to 3 km from the source is almost independent of the composition of the harmonics emitted by the vibrator or formed in the zone adjacent to it, but is determined only by the conditions of nonlinear propagation in the extended path.

Near the source, at distances of a few hundred meters, formation of nonlinear effects occurs basically as shown in [9], in an intense surface wave. At distances of 1 km or more in this same frequency range, as the results of our investigations show, body waves, exiting to the surface at rather steep angles, make a substantial contribution to the nonlinear structure of the wave field. These waves, propagating along extended paths, undergo a long accumulation of nonlinear distortions. Thus far, it is still an open question as to what distances there is a substantial contribution of nonlinear effects to the dynamics of vibrosignals.

Some of the results obtained concerning the generation of powerful low-frequency signals in the medium as a result of interaction of high-

frequency primary waves (see for example Fig. 4) indicate the promise of low-frequency parametric studies of seismic waves [8, 16], which have found wide application in nonlinear acoustics. It is possible that this will permit solving one of the existing technical problems of vibrational illumination of the earth.

Further investigations of nonlinear seismic phenomena should be related to detailed study of them at points internal to the medium and at the surface with the goal of elucidating concrete wave types, depth intervals, rock types, and their structural and textural features, with which the nonlinear interactions are principally related. A precise quantitative model of nonlinear seismic phenomena is still far from complete. The goal of studying these phenomena, as presented, should in the final analysis be the solution especially of the practical problems, for example creation of survey methods of studying a nonlinear parameter as a geologically informative characteristic of the medium or the solution of technical problems in parametric emission and reception of seismic waves. The results of these investigations can be useful when refining existing and creating new methods in traditional vibrational seismic surveying where the influence of nonlinear effects on the formation of the wave field of vibrosources is considered.

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