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The nonlinear wave effects in vibroseismics

M.S. Khairetdinov

The process of radiation of seismic wave fields generated by powerful seismic vibrators is accompanied by a number of physical phenomena taking place in the vicinity of a source and having continuation at significant distances from it. The present paper is dealt with the analysis of these phenomena and the estimation of their quantitative characteristics.

Alongside with a seismophysical field, the radiating "vibrator-ground" system generates acoustic and electromagnetic fields [1, 2]. In this connection, the authors show that the acoustic signals can be recorded (under certain atmospheric conditions) at distances of tens kilometers from a source [1]. Seismoelectromagnetic signals were recorded in a near zone [2]. The mechanism of their excitation is connected with the action of a seismic wave on the magnetic sensor.

Coincident with processes of excitation by vibrators of the fields of various physical nature the nonlinear physical effects occur in the source zone resulting in appearance of the lower and the higher multiple frequencies in seismic oscillations. Such effects are caused by specific features of the construction of a definite type of a source, as well as by processes of interaction of a source with ground and, also, by mechanical properties of the latter. For example, the nonlinear effects of radiation inherent to the vibrator CV-100 are caused first of all by the violation of the condition of continuity of the vibrator with the underlying surface.

The oscillations of a seismic vibrator are described by the equation

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

Here m is the mass of the vibrator, F is the excitation force, $P_0 = mg$ is the weight of the vibrator, $k(u)$ is rigidity of a medium, R is the active resistance of radiation, u is the vibrator platform offset. In the case when $F > P$, there is a separation of the radiating platform of the vibrator from the underlying surface. At the moment of the separation, the offset of the vibrator $u = 0$. At $u < 0$, the source is in free fly. The condition of continuity of a source with a medium is determined by the condition: $u \geq 0$. The separation of the vibrator from a medium is cause of the occurrence of nonlinear effects causing harmonics in a vibroseismic signal.

The other possible reasons for the occurrence of the physical nonlinearity of radiation are due to the type of the construction of a certain vibrator, or, when the rigidity of the underlying surface is a nonlinear function of displacement of the vibrator platform. In particular, as for the hydroresonant vibrator HRV-50, the nonlinear effect of radiation is primarily due to nonlinear properties of a pneumatic opposing spring, supporting the oscillatory mass as water column [4].

An additional possible cause of the physical nonlinearity of radiation for all powerful vibrators is of the phase non-coincidence of the interaction of separate parts of the vibrator platform with the ground surface.

The full seismic radiated power from the vibrator makes:

$$N_\Sigma = \frac{1}{2}|F|\,|\nu|\cos\varphi, \tag{2}$$

where $\nu = \dot{u}$, φ are the vibration velocity of the surface and the phase angle between the exciting force and velocity, respectively.

In case of the nonlinear radiation condition the full radiation power is redistributed between the basic radiation frequency and harmonics:

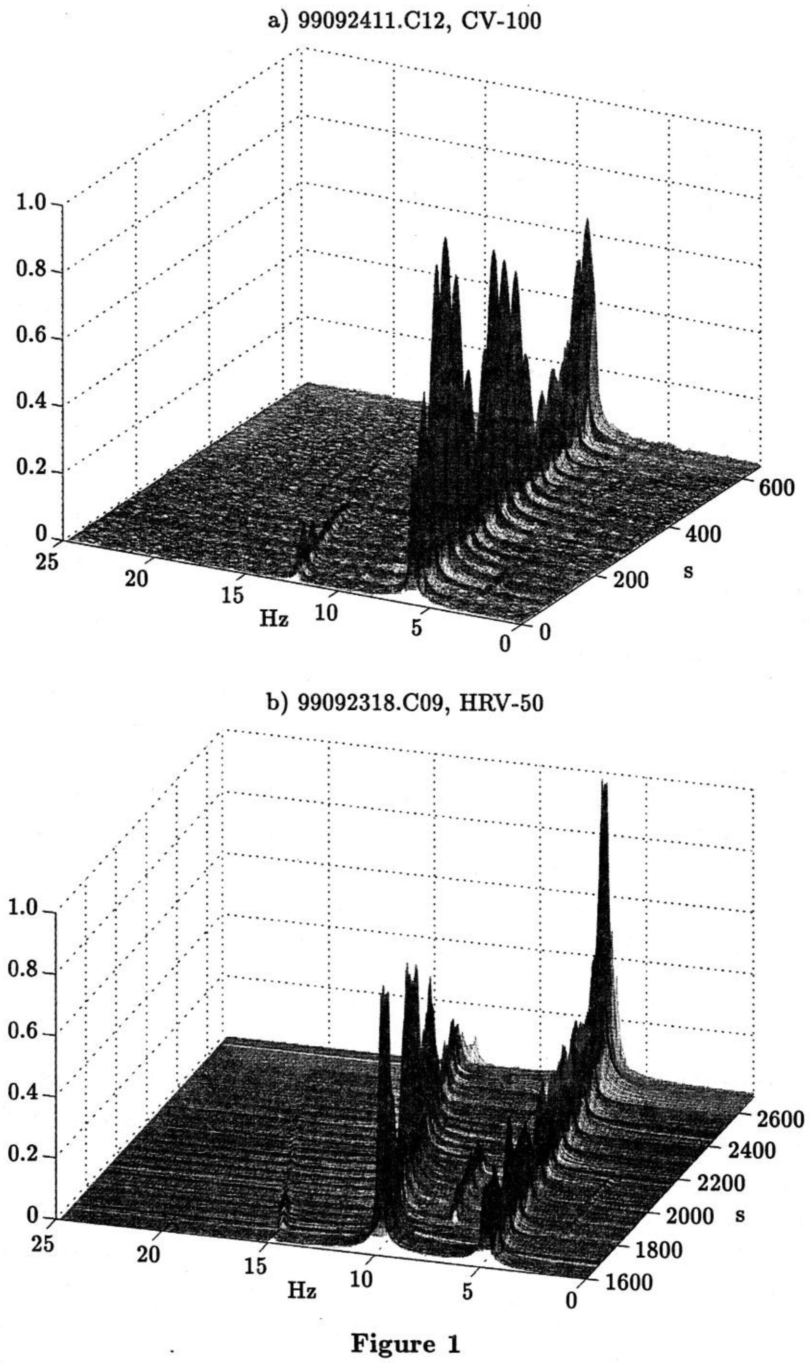
$$N_\Sigma = \frac{1}{2}\Big(|F_0|\,|\nu_0|\cos\varphi_0 + \sum_{i=1}^{N}|F_i|\,|\nu_i|\cos\varphi_i\Big). \tag{3}$$

Here F_0, ν_0, φ_0, F_i, ν_i, φ_i are the exciting force, the displacement velocity of ground and the phase angle between them on the higher harmonics.

Experiments

For the estimation of the quantitative characteristics of the nonlinearity effects in the fields under study, experiments connected with simultaneous recording of seismic, acoustic and electromagnetic fields, generated by the vibrators CV-100 and HRV-50 were carried out. For the recording of fields of different physical nature, the short-period seismic receiver with the transformation coefficient 150 v/m/sec, the acoustic piezoelectric pressure gauge with the transformation coefficient 200 μv/Pa and high-sensitive magnetic sensor were used. The nearest to vibrators seismic receiver was at a distance of 400 m from the sources. The radiation modes included the monochromatic signals with a set of discrete frequencies and sweep-signals.

The nonlinearity effects of seismic oscillations radiation were estimated with the help of spectral-temporal functions, which were calculated in relation to sweep-signals, radiated by the vibrator. The vibrator CV-100 radiated a signal with a frequency band 6.25–9.5 Hz during 600 s. The spectral-temporal function of such a signal is shown in Figure 1a. The calculation



a) 99092411.C12, CV-100
1.0
0.8
0.6
0.4
0.2
0
25
20
15
Hz
10
5
0
0
200
400
600
s
b) 99092318.C09, HRV-50
1.0
0.8
0.6
0.4
0.2
0
25
20
15
Hz
10
5
0
1600
1800
2000
2200
2400
2600
s

Figure 1

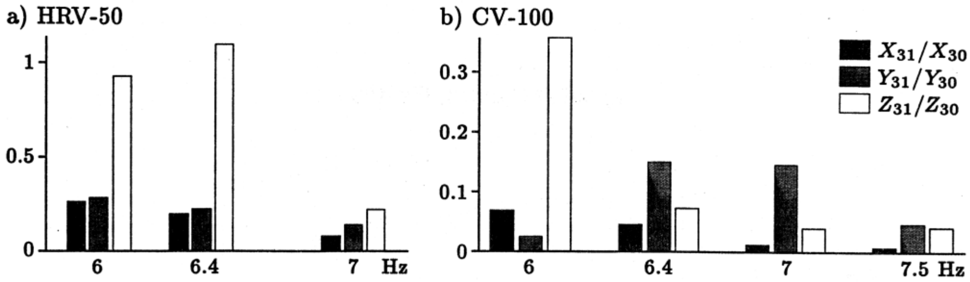


Figure 2

of such a function is carried out in the time-sliding window during 10 s. The function of the same type for the vibrator HRV-50 is represented in Figure 1b. The latter function is obtained for a sweep-signal with a frequency band 5–7 Hz during 1.400 s. In both cases the spectral-temporal functions are obtained for the vertical component Z.

The nonlinearity effects of radiation for all the components X, Y, Z are represented as histograms in Figure 2. The height of each column in the histogram corresponds to the ratio of the amplitude of the second harmonic to the amplitude of the basic frequency (coefficient of nonlinearity). A set of the basic frequencies (in Hz) is represented on the abscissa axis. The correspondence of the histograms to the components X, Y, Z is illustrated in the upper right corner of the figure. The obtained results, represented in Figures 1 and 2, are in full agreement. According to the presented histograms, the level of nonlinearity of the vibrator HRV-50 is the highest, especially, for the components Z and Y. In this case, the nonlinearity coefficient reaches 100%. The appropriate nonlinearity coefficients for the vibrator CV-100 are about 3 times lower (see Figures 1a and 1b).

The nonlinearity effects, showing up in the first place on the component Z, are associated with the vertical polarization of the exciting force generated by both types of vibrators.

The physical nonlinearity of radiation recorded in the nearest to vibrators zone, has its continuation in remote zones, i.e., on the spacing intervals essentially exceeding a wavelength of seismic oscillations. For the estimation of these effects the ratios of the levels of vibrational seismograms obtained simultaneously on the second and the basic harmonics in sounding modes by monochromatic and sweep-signals were calculated.

The histograms, illustrating the relation between the amplitudes of the second and the basic harmonics, which are characterized as nonlinearity coefficients, for monochromatic signals of frequencies 6.0, 6.5, and 7.0 Hz, are represented in Figures 3a, 3b, and 3c, respectively. Oscillations were recorded by the three-component seismic receivers at distances of 0.3, 20, 25, 35, 60, 70, 320 km, the component X being oriented strictly to the source.

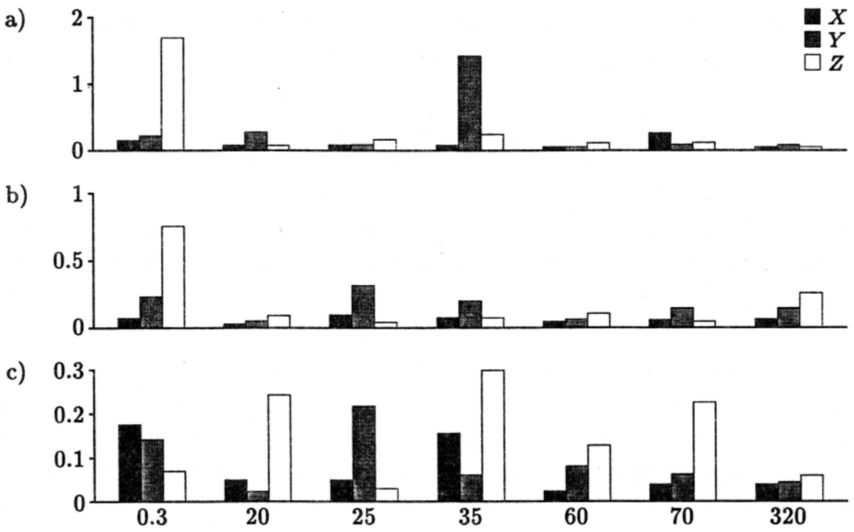


Figure 3

The nonlinearity coefficients were obtained for the three components X, Y, Z. The appropriate histogram columns for these components are marked to the right of the histograms.

Analysis of the demonstrated histograms implies the following:

- the highest level of the second harmonics is observed on the components Z and Y;
- the nonlinearity effect for Z-component is concerned with the vertical polarization of the disturbing force generated by the vibrator CV-100;
- the most significant nonlinearity effect is achieved on the frequencies closest to resonance. In this case, it place on the frequency $f = 6.75$ Hz. As is seen from Figures 3b and 3c, the nonlinearity effect for Z- and Y-components is expressed at all the recording points at distances of 0.3÷320 km. In this case, with increasing the distance, the nonlinearity effect even enhances, which is characterized by an increment in the nonlinearity coefficients.

The presented results indicate to the two mechanisms as sources of nonlinearity. The first is stipulated by the nonlinearity of radiation and is connected with separation of the vibrator from the ground, when the radiation frequency is close to the resonant frequencies. This is confirmed by a high level of the second harmonics on these frequencies in the nearest to vibrators zone, which reaches 70% and higher (see Figures 3a, 3b).

The second mechanism is due to a medium of seismic waves propagation, which is exhibited by the accumulating nature of nonlinear distortions. Thus, the harmonic component oscillations register in body waves, elapsed large path. Really, as shown in [5], the displacement amplitude of a second harmonic originating in a longitudinal wave, makes:

$$A_{P2} = \frac{kR\omega^2 A_{P1}^2}{8v_P^2}.$$

Here k is the nonlinearity coefficient of the medium, A_{P1}, ω, v_P are amplitude, frequency, and velocity of the primary wave propagation, R is the path, travelled by it.

As follows from the above ratio, the level of a second harmonic is proportional to the length of the path. This is responsible for the nonlinearity effect accumulating in the medium. This is confirmed by the data of Figure 3c. It is necessary to note that the action of the first mechanism results in the extension of the spectrum of frequencies of sounding oscillations towards high frequencies. The high frequencies being rapidly absorbed by the medium with distance.

The second mechanism, in turn, is favorable to accumulating the nonlinear effects with distance. The research into the scope of both mechanisms is of interest. However this problem does not come within the province of this paper.

The estimations of the nonlinearity coefficients in the vibrational seismograms as a result of the ratio of amplitudes of convolutions of the sounding sweep-signals on the second and the basic harmonics with recorded signals were obtained. The range of the basic frequencies of the sweep-signal is within 5.5÷8.5 Hz. Appropriately, a sweep-signal of the second harmonics is within the band 11÷17 Hz. In Figure 4, the vibrational seismograms, obtained in the indicated bands for the components X, Y, Z at distances of 20 and 50 km, are demonstrated.

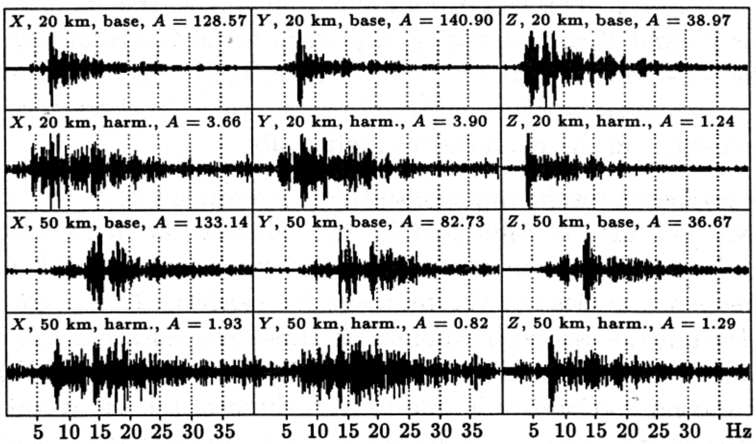


Figure 4

These seismograms are characterized by the following features:

- the dominant level and the higher contrast in arrivals of the waves P on Z-component in the field of the second harmonics. This is explained by the dominant spectrum of P-waves, which is concentrated in a high-frequency area, including the field of the frequencies of the second harmonics. The marked features are observed at both distances – 20 and 50 km;

- the dominant contribution of the second harmonics in relation to the basic ones as well as earlier is observed on Z-component and is about 3%. Their contribution on the components X, Y makes less than one percent.

Taking into account the contribution of the second harmonics of sounding signals to the levels of oscillations recorded in nearest and remote zones, it is necessary to consider them when studying the nonlinear effects caused by the medium of wave propagation, and, also, when selecting waves P, S based the treatment of oscillations of the basic and higher harmonics.

The acoustic and seismomagnetic fields in the zone of the vibrators CV-100, HRV-50 were recorded simultaneously with recording of vibroseismic oscillations. In relation to the vibrator CV-100 the recording was carried out in the radiation mode of a sweep-signal in the frequency band 6.25–9.57 Hz at a sweep length 900 seconds. The results of the processing as correlations convolution between reference and seismic (vibrational seismogram), reference and acoustic (vibrational acoustogram) signals are shown in Figure 5.

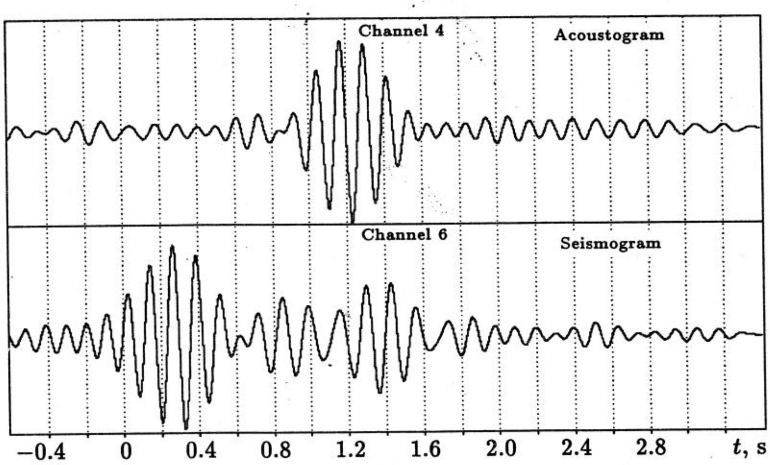


Figure 5

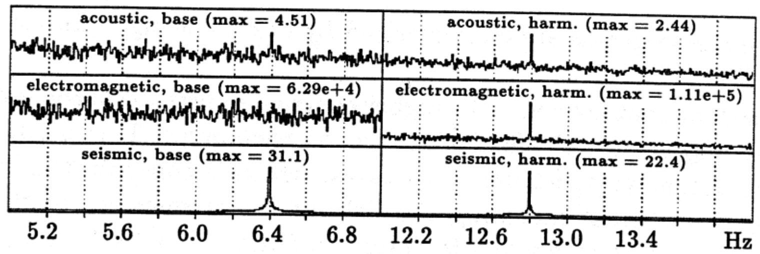


Figure 6

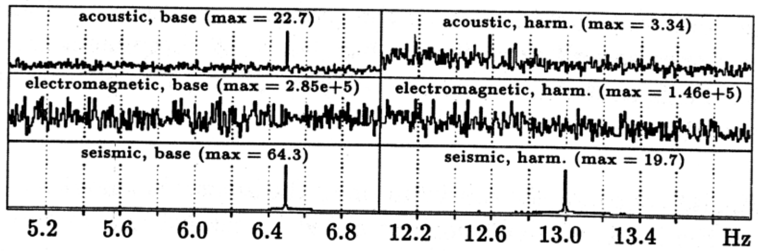


Figure 7

The maximum of a vibrational acoustogram corresponds to 1.2 seconds. To this time corresponds the distance "source–receiver", equal to 400 m. From Figure 5 it is clear that the acoustogram has a simple shape and is represented as one wave. At the same time the seismogram has a more complicated shape, which indicates to a layered structure of the medium in the zone of the vibrator. At least three reflected waves are distinguished in the seismogram.

The results of the simultaneous recording of seismic, acoustic and seismomagnetic fields, radiated by both types of vibrators, are illustrated as spectrograms of signals, recorded in the monochromatic modes of radiation on a number of fixed frequencies. Figures 6 and 7 present the amplitude spectra of signals and noise, obtained in the frequency band 0–25 Hz.

The sounding signals are radiated by the vibrator HRV-50 with frequency 6.4 Hz (see Figure 6) and by the vibrator CV-100 with frequency 6.5 Hz (see Figure 7).

From the analysis of the presented here and the earlier obtained results it follows that the nonlinear effects connected with the occurrence of higher harmonics, can take place in all the three types of fields. As opposed to a seismic field, the nonlinearity in acoustic and seismomagnetic fields has unstable character and depends on the type of a source and the mode of radiation. The nonlinearity effects are most typical of the vibrator HRV-50 and are due to the most distinct nonlinearity of the mode of radiation of the given type of a source.

Conclusion

1. The physical nonlinearity of the process of radiation of vibroseismic sounding signals is stipulated by a number of reasons: the constructive scheme of a certain type of the vibrator, violation of the condition of continuity of a source with underlying surface, nonlinearity of the rigidity characteristic of the medium under the vibrator, etc. As is shown, by virtue of the nonlinearity of radiation, the multiple frequencies (the higher harmonics) are recorded both in near, and in distant zones. On an example of the powerful centrifugal vibrator CV-100 the ratios of levels of the second harmonics of a vibroseismic signal to the basic harmonics (coefficients of the nonlinearity) in the modes of sounding by harmonic and broadband oscillations at distances of 0.3–300 km are presented. The highest values of coefficients are observed on the components Z, Y in the field of the resonant frequency (about 7.0 Hz), inherent to the given chain "the vibrator – ground". Here the values of the nonlinearity coefficients vary from 100% in the nearest zone to 5–20% in the remote zone (320 km).

2. On the basis of experimental studies, the quantitative estimations of nonlinear effects of radiation in seismophysical, acoustic and seismomagnetic fields in the radiation zone of the powerful vibrators CV-100, HRV-50 are obtained.

3. The observed effects of nonlinearity should be taken into account when studying the physical nonlinearity excited by the medium of distribution of seismic waves, and, also, for increasing the efficiency of selection of longitudinal waves in vibrational seismograms.

4. Finally, relevant is the problem, associated with separation of the contribution of a source and a medium to the aggregate effect of nonlinearity, observed at the point of recording. The solution of this problem is a valid one for further investigation.

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