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Spatial dynamics of frequency-temporal characteristics of seismic waves from powerful vibrators

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The given work is aimed at the analysis of features of spectral-temporal functions (STF), describing vibrational seismograms from powerful vibrators in the near and far zones. The spectral characteristics of P- and S-waves in a far zone at distances of 50, 320, 355 km have been analyzed. The phenomenon of redistribution of oscillation levels between P- and S-waves with respect to a distance has been analyzed too.

For the solution to many seismic problems: monitoring of seismic-prome zones, seismic tomography, seismic calibration of seismic traces and seismostations [1], etc., connected with application of powerful vibrators, it is necessary to study the dynamics of processes of generation of seismic fields in the near and far zones covering distances from tens of meters up to hundreds of kilometers. Such processes should be described by multidimensional functions, in which time is a constant parameter. One of such functions is a 2D the spectral function of a seismic signal given as a set of discrete values $S_n = S(t_n)$, $n = 0, \ldots, Q-1$. The characteristic values Q at deep seismic sounding (DSS) by extended long-duration sweep-signals make 2 Mb, with the scanning rate in frequency being 0.001 Hz/s. Let us partition a set of the values Q to L subsets each of N dimension. Then as a 2D spectral-temporal function we consider a function of the form

$$F(k,l) = \sum_{n=0}^{N-1} S_l(t_n) \exp\left(-i\frac{2\pi nk}{N}\right), \qquad l = 1, \ldots, L. \tag{1}$$

The essence of the given procedure of the analysis is in that the continuous signal $S(t)$ is partitioned in time to the sections $S_l(t)$, each with duration $T = N\Delta t$, where Δt is the interval of quantization, and for each section the values of the spectrum in N spectral windows of the size $\Delta f = 1/T$ are calculated.

Such a description can be used only for a near zone, i.e., for the description of seismic oscillations recorded near the vibrator. In a far zone that is hundreds of kilometers away from a source, the seismic signal is overlapped by the noise, much more intensive in its level, therefore in this case only the vibrational seismogram $r(m)$ is subject to the 2D spectral-temporal description calculated as convolution of a signal S_n with a basic signal z_n, restored at the recording point according to the law of unsweeping of a sounding signal of the vibrator:

$$r(m) = \frac{1}{N_1 - m} \sum_{n=0}^{N_1-m-1} S_n z_{n+m}, \qquad m = 0, \ldots, N_1. \tag{2}$$

In this case the spectral-temporal function by analogy with (1) takes the form

$$G(k,l) = \sum_{m=0}^{N_1-1} r_l(m) \exp\left(-i\frac{2\pi mk}{N_1}\right), \qquad l = 1, \ldots, L_1. \tag{3}$$

The given work is aimed at the analysis of features of spectral-temporal functions (STF) of the form (1), (3), describing vibrational seismograms from powerful vibrators in the near and far zones. As vibrational sources powerful, low-frequency vibrators: the centrifugal vibromodule CV-100 with the acting force of amplitude 100 ton [2], the centrifugal vibromodule CV-40 with the force 40 ton, the hydroresonant vibrator HRV-50 with the force 50 ton [3] are chosen.

The spectral-temporal functions (1) of oscillations recorded near to vibrators (at a distance of 30 m), are presented in Figures 1a, 1b for CV-100 and HRV-50, respectively. The presented 2D graphs reflect the dynamics of radiation in time, which is connected, first of all, with redistribution of the radiation power in the basic frequencies and their harmonics.

The vibrator HRV-50 has the most significant redistribution of the radiation power between the basic frequencies and their second harmonics in the whole range of the scanning frequencies of a sounding signal (4–7 Hz). This is connected, first of all, with a nonlinear mode of excitation of oscillations by a source of this type [2]. The second harmonics of the vibrator CV-100 are most expressed for the basic frequencies in the field of the resonant radiation of the vibrator/medium circuit in the area of 6.8–7.0 Hz. The occurrence of the second harmonics in this situation is explained by an insignificant separation of a source from the underlying surface, which is the reason of nonlinearity with perturbation of oscillations in the medium.

It is obvious that the use in recordings of the second harmonics spectrum in a distant zone will additionally contribute to the energy of a vibrational seismogram, raising its noise stability.

Let us dwell on the dynamics of spectral-temporal functions (STF) in a far zone covering the recoding stations at the distances of 50, 320, 355 km from the vibrator CV-100. Such functions are presented in Figures 1c, 1d. In both graphs the spectra of P- and S-waves corresponding to the arrival time $t_p = 8.5$ s, $t_s = 14.5$ s on the component Z for the distance of 50 km and $t_p = 48$ s, $t_s = 84$ s for 320 km are distinct.

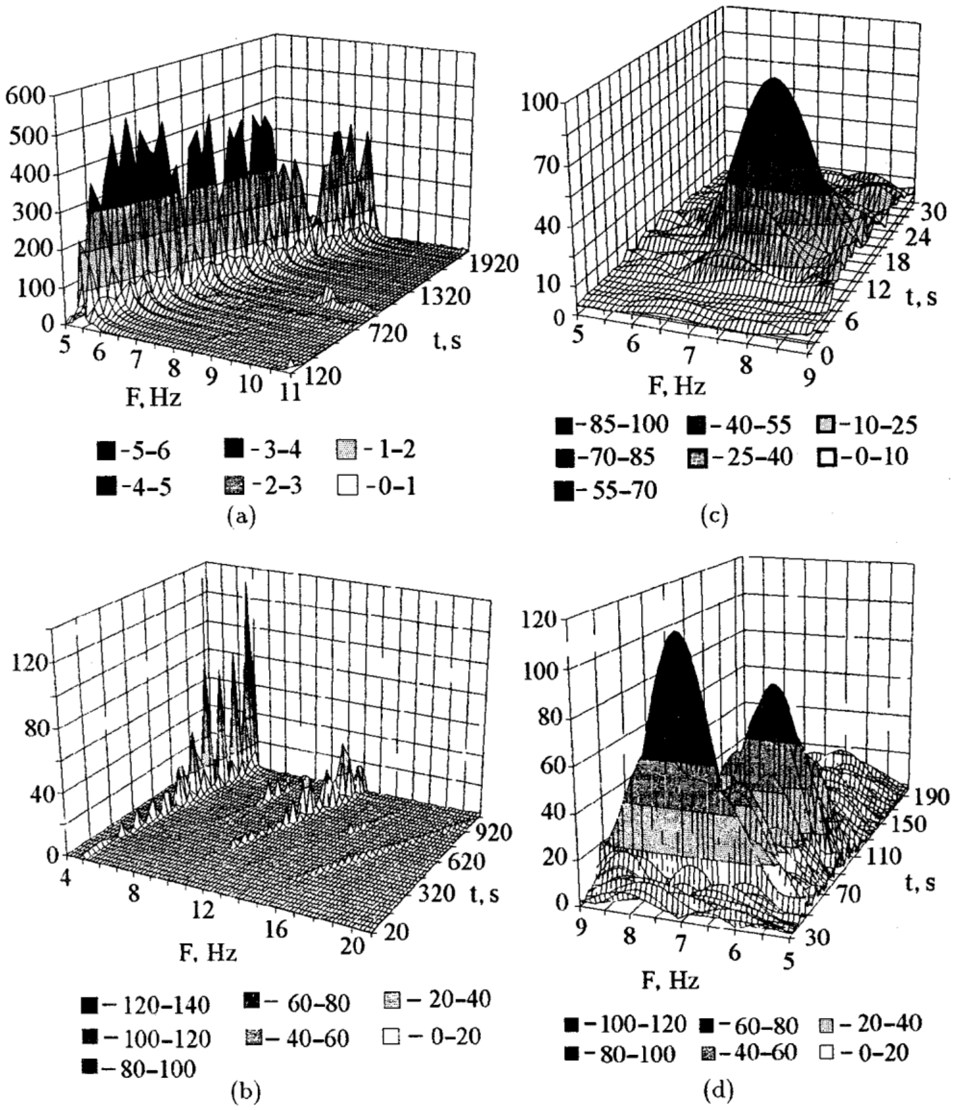

Figure 1. STF (1) for the vibrators (a) CV-100 and (b) HRV-50; STF dynamics in far zone for the vibrator CV-100 at the distance (c) 50 and (d) 320 km

As follows from the analysis of the graphs in Figures 1a, 1c, 1d, the farther the distance from a source, the narrower the spectra of P- and S-waves on the one hand, and a relative displacement of their maxima among themselves is such, that the maximum of the spectrum of P-wave locates in the domain of high frequencies, while the spectrum of S-wave – in the domain of low frequencies of the sounding signal. These regularities are illustrated by graphs of the spectra of P- and S-waves referred to distances 50, 320, 355 km. The graphs are presented in Figures 2a, 2b, 2c, respectively.

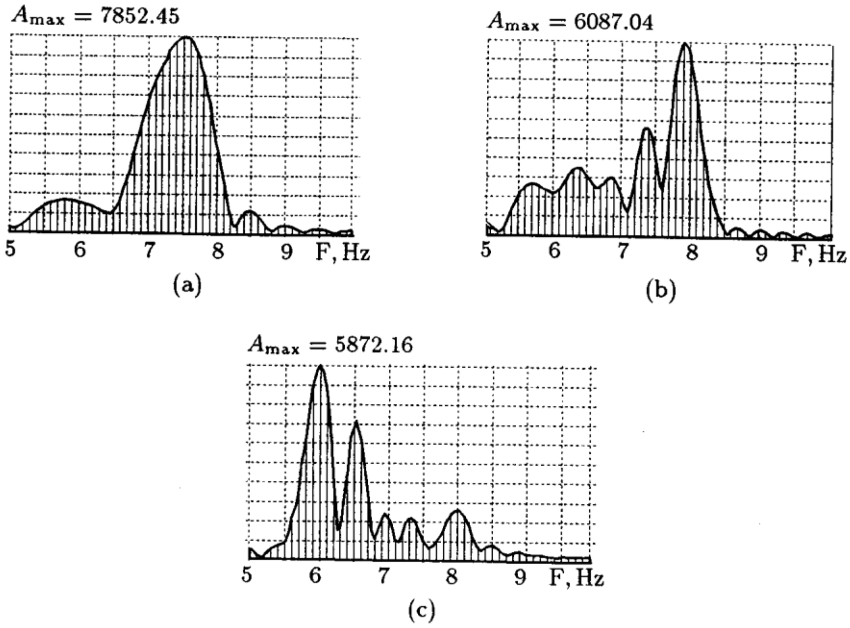

Figure 2. Graphs of the spectra of the waves for the distances (a) 50, (b) 320, and (c) 355 km

In particular, it is seen from the figures that the spectrum of the sounding signal of the vibrator CV-100, concentrated within the band 5.5–8.5 Hz (see Figure 1a), is becoming narrower at a distance of 355 km up to 0.5 Hz for P-wave and 0.8 Hz for S-wave. Thus, the maxima locate on frequencies of 7.8 and 6.2 Hz, respectively. The revealed frequency dependence of P- and S-waves can be used for division of the both types of waves according to the frequency feature alongside with division of waves according to the times of their arrivals. For the latter case the STF of vibrational seismograms, distinguished according to (3) and corresponding to a distance of 320 km, are shown in Figures 3a, 3b, 3c – for the components X, Y, Z, respectively.

The right part of each of the given figures represents a projection of values of spectra onto the frequency/time plane. In this case the indicated closed isolines reflect the levels of equal values of the spectra. Let us call such a representation of spectra the 2D a projective spectrum or, for simplicity, the projective spectrum. On a projective spectrum it is possible to define more precisely the arrival times t_p, t_s based on separation of the maxima spectra F_{mp}, F_{ms} of P- and S-waves. Thus, in Figure 1a the most dense areas of a projective spectrum corresponding to the maxima of spectra of P- and S-waves, refer to the times 48 and 84–87 s, that corresponds to the times of arrival of P- and S-waves. The graphs similar to the given ones, were obtained for vibrational seismograms as well, that are referred to recording stations at distances of 50 and 355 km.

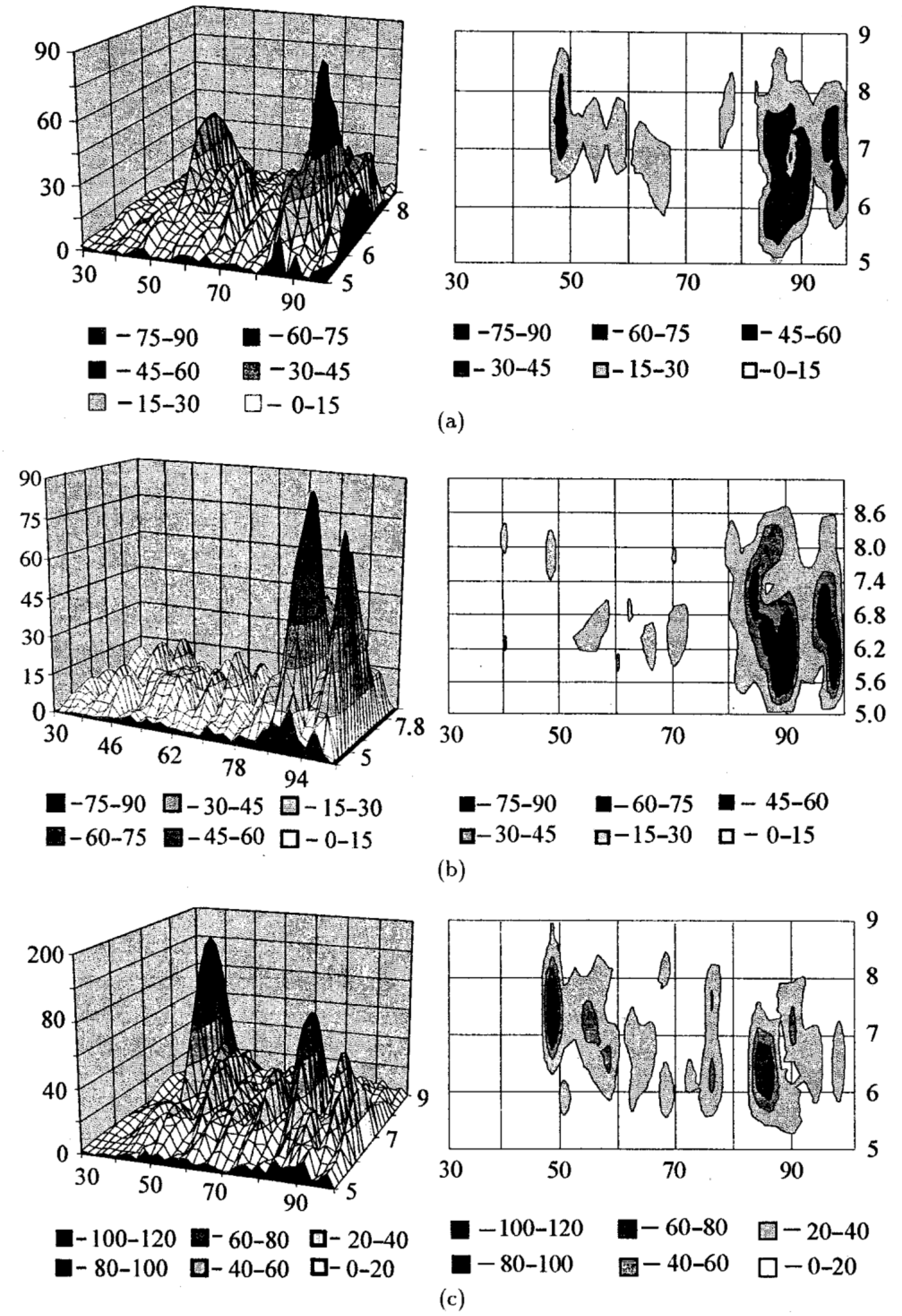

Figure 3. STF (3) at the distance 320 km for (a) X, (b) Y, and (c) Z components

Let us discuss some features of the obtained spectral-temporal representations. First, the most dense on the time axis are spectra of P- and S-waves, obtained by the components Z, X, with the sharpest arrival of P-wave on the components Z being observed (Figure 3c). As the analysis of the figures shows, this is due to the fact that there is a number of other reflected waves between the arrival times t_p, t_s, which smear the picture of arrivals of S-waves. With increasing the distance the ratio between the maxima of P- and S-waves along the component Z increases from 0.25 to 50 km and from 1.3 to 355 km. As for the component X, such a growth is not observed. P-wave is absent on the component Y. The given numerical values on the dynamics of the spectral-temporal characteristics of seismic waves are given in the table.

Distance, km	F_{mp}/F_{ms}			Signal/noise for P			Signal/noise for S		
	Z	X	Y	Z	X	Y	Z	X	Y
50	0.25	0.4	—	4	2.5	—	7.5	8.1	6.7
320	1.37	0.47	—	14	7.0	—	10.0	12.0	8.8
355	1.33	0.6	—	4	4.8	—	5.6	7.3	11.0

Here F_{mp}/F_{ms} is the ratio of the maxima of the spectra obtained for P- and S-waves; the ratio signal/noise characterizes the ratio of the maxima of spectra of P- and S-waves to the mean-quadratic value of noise. Numerical values of the latter generally exceed similar parameters obtained for the initial vibrational seismograms since spectral-temporal functions are calculated as a result of additional filtration of the initial seismogram within the limits of the given temporal window Δt set in (3).

Conclusion

1. The spectral-temporal characteristics of sounding signals of powerful low-frequency vibrators CV-100, CV-40, HRV-50 have been analyzed. The effect of redistribution of the seismic energy between the basic and higher-frequency harmonics of the vibrator HRV-50 within the whole band of sounding (4–7 Hz), of the vibrator CV-100 has been revealed in the field of resonant frequencies. The account of this effect in recordings in a far zone will improve the quality of vibratonal seismograms.
2. The spectral characteristics of P- and S-waves in a far zone at distances of 50, 320, 355 km have been analyzed. The values of narrowing of a band of frequencies of sounding signals with distance due to resonant properties of a wave propagation medium have been estimated.
3. A regularity connected with redistribution of the maximum oscillation power in the high-frequency domain (7.5–8 Hz) in the spectrum of

P-waves and of the lower frequencies (5.5–6.5 Hz) to the spectrum of S-waves within the limits of the frequency band of sounding (5.5–8.5 Hz) has been revealed. This regularity will encourage the division of P- and S-waves in the vibro-DSS tasks not only according to the temporal, but also according to the frequency feature.

4. The phenomenon of redistribution of oscillation levels between P- and S-waves with respect to a distance has been analyzed. The increase of the ratio of levels of P- and S-waves on the component Z from 0.25 to 50 km up to 1.33–1.37 to 320 and 355 km is marked. On the components X, Y the ratio of levels does not vary.

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