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Analysis of P- and S- wave arrival times on harmonic and broad-band vibroseismic signals

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The recently developed method of active vibroseismic monitoring is based on the sounding of a geological structure by seismic waves from artificial controlled sources – vibrators. Thus, the changes occurring in the tensely-deformed state of a medium are considered as related to changes of information parameters of wave fields that are established in the medium with long radiation by the vibrator of broad-band sweep or harmonic signals.

When realizing monitoring on large areas of observation making hundreds of kilometers, there are natural restrictions of an opportunity to detect a weak variability of a medium from the analysis of temporal variations of parameters of seismograms. Such restrictions are due to the fact that with the finite capacity of vibrating sources and a limited frequency band with increasing the distance the signal/noise ratio decreases, and consequently, the contrast of vibrational seismograms decreases, too. Thus, accordingly, the accuracy of defining the amplitude, temporal and polarization characteristics of separate waves is reduced. When realizing the vibroseismic method it is possible to overcome the specified difficulties at the expense of the increase of the time of vibrations [6]. The sensitivity to inessential changes of the mechanical characteristics of a medium in the method of active monitoring is provided due to high metrological characteristics of the vibrational sources of seismic waves. Thus, high noise-stop feature of the vibroseismic method and, consequently, the possibility of increasing the range of sounding are attained in the sounding mode by narrow-band signals [6]. At the same time with application of such signals there arises a well-known problem of separation of seismic waves according to their arrival times.

In the present work we discuss one of possible approaches to solving the given problem, which is based on consideration of features of spectra of the P- and S-waves, and analyze the results of measurements of the travel times of the basic types of waves obtained with the vibroseismic sounding using broad-band and narrow-band signals. The comparative analysis of the results allows us to make a conclusion about a possibility of separation of types of waves when using monochromatic signals. Let us dwell on this statement.

Let us present a vibroseismic signal recorded at the receiving point, as

$$a(t) = S(t) * F(t) * H(t) + n(t), \tag{1}$$

where $S(t)$ is a controlling signal, $F(t)$ is operator of the filter taking into account the influence of mainly the systems "vibrator–ground" and "ground–seismic sensor", $H(t)$ is the impulse characteristics of the medium, $n(t)$ is a set of additive noise, "$*$" is a convolution sign. A vibrational correlative trace represents a trace with a basic signal:

$$R(\tau) = r_s(\tau) * F(t) * H(t) + n_s(\tau), \tag{2}$$

where $r_s(\tau)$ is a function of autocorrelation of a controlling signal, $n_s(\tau) = S(-t) * n(t)$ is the noise, correlated with a controlling signal. Within the frequency range the correlated trace (2) will be written down as:

$$R(\omega) = r_s(\omega)F(\omega)H(\omega) + n_s(\omega), \tag{3}$$

where $r_s(\omega)$ is the spectrum of power of a controlling signal; $F(\omega)$ is a transmission gear function of the systems "vibrator–ground" and "ground–seismic device"; $H(\omega)$ is a transmission function of the medium; $n_s(\omega)$ is spectrum of power of noise.

From (2) and (3) follows that both in the temporal and in the frequency domains the correlogram trace can be divided into three parts: information content, determined by interaction of a sounding signal with a medium, the distorting influence of the system "vibrator–ground" and the noise in the frequency band of a controlling signal (microseismic noise and technogenic noise).

In order to characterize the dynamics of a vibrational seismogram in the frequency–temporal domain let us make use of the concept of an instant spectrum, which is defined as follows [5]:

$$S_T(\omega, t) = \int_{t-T}^{t} f(\tau)e^{-j\omega\tau}d\tau, \tag{4}$$

i.e., the instant spectrum is defined as spectrum of a part of the process of duration T directly preceding the given moment t. Let us partition trace (2) into n pieces of duration T each so, that

$$t_i = Ti, \qquad i = 0, 1, 2, \ldots, n-1. \tag{5}$$

Then with a sufficiently large n expression (3) can be considered as an instant spectrum of the form

$$R(\omega, t_i) = r_s(\omega, t_i)F(\omega, t_i)H(\omega, t_i) + n_s(\omega, t_i), \quad i = 0, 1, 2, \ldots, n-1. \tag{6}$$

The application of instant spectra for the analysis of impulse seismic traces [3] is well-known, which is also useful as applied to vibrational correlated traces.

Figure 1 presents the results of processing of seismic signals recorded by a three-component seismic receiver at a distance of 320 km from the vibrator CV-100, acting onto the ground with the force of 100 tons. The data were obtained in the course of the Russian–Japanese experiment on studying the structure of a vibroseismic field [2]. In the upper part of Figure 1, the vibrational correlated traces with respect to the components x, y, z are shown, obtained by the sweep-signal radiation of 43 m duration within the frequency band of 5.5–8.5 Hz. The analysis of these correlotraces shows that at the 48-th second on the components x and z the first arrival of the P-wave, refracted from the Moho boundary is distinct. In a far part of correlated traces at the recording times $t = (1.73 \div 1.75)t_p$ on all the components x and z the groups of intensive waves identified as various types of S-waves are clearly seen. Directly under the correlated traces their instant spectra of the form of (6) are shown. For the construction of spectra the correlated traces were partitioned into 5-second intervals, and on each of them there was found a selective spectrum with a frequency step of 0.2 Hz. The spectra are presented as lines of an equal level, with a step of 0.2 of the maximal value. On the time intervals appropriate to separation of S-waves the spectral maxima on all the three components are observed. On the intervals appropriate to separation of P-waves the maxima on all the three components are observed. A significant non-uniformity of spectra, especially for S-waves, is explained by a filtering action of the terms $F(\omega, t_i)$ and $H(\omega, t_i)$ in expression (6).

It is seen from Figure 1 that instant spectra of the correlated traces on the components x and z and in the field of P-waves have the maximal spectral density on the frequencies higher than 7 Hz, and in the field of S-waves – on the frequencies lower than 7 Hz. This phenomenon can be made use of for separation of waves in the vibroseismic monitoring on harmonic signals. In order to confirm this conclusion experimentally let us use the results of monitoring on harmonic signals. In the experiment a series of harmonic signals included six portions of 10 min duration each within the range of 6.00–7.25 Hz with a frequency step of 0.25 Hz. The spectra of recorded signals on the three components are given in the bottom of Figure 1. For definition of the type of a wave, predominantly transferring the energy, the travel time on each of the six frequencies as well as on each of the three spatial components was measured. The measurements were made with the help of the well-known algorithm of the quadratic accumulation of signals (phase detection) [4]. The moment of time of the beginning of a charge of accumulation and stabilization of a phase, as well as the moment of the beginning of its discharge was determined. The equality of the travel times

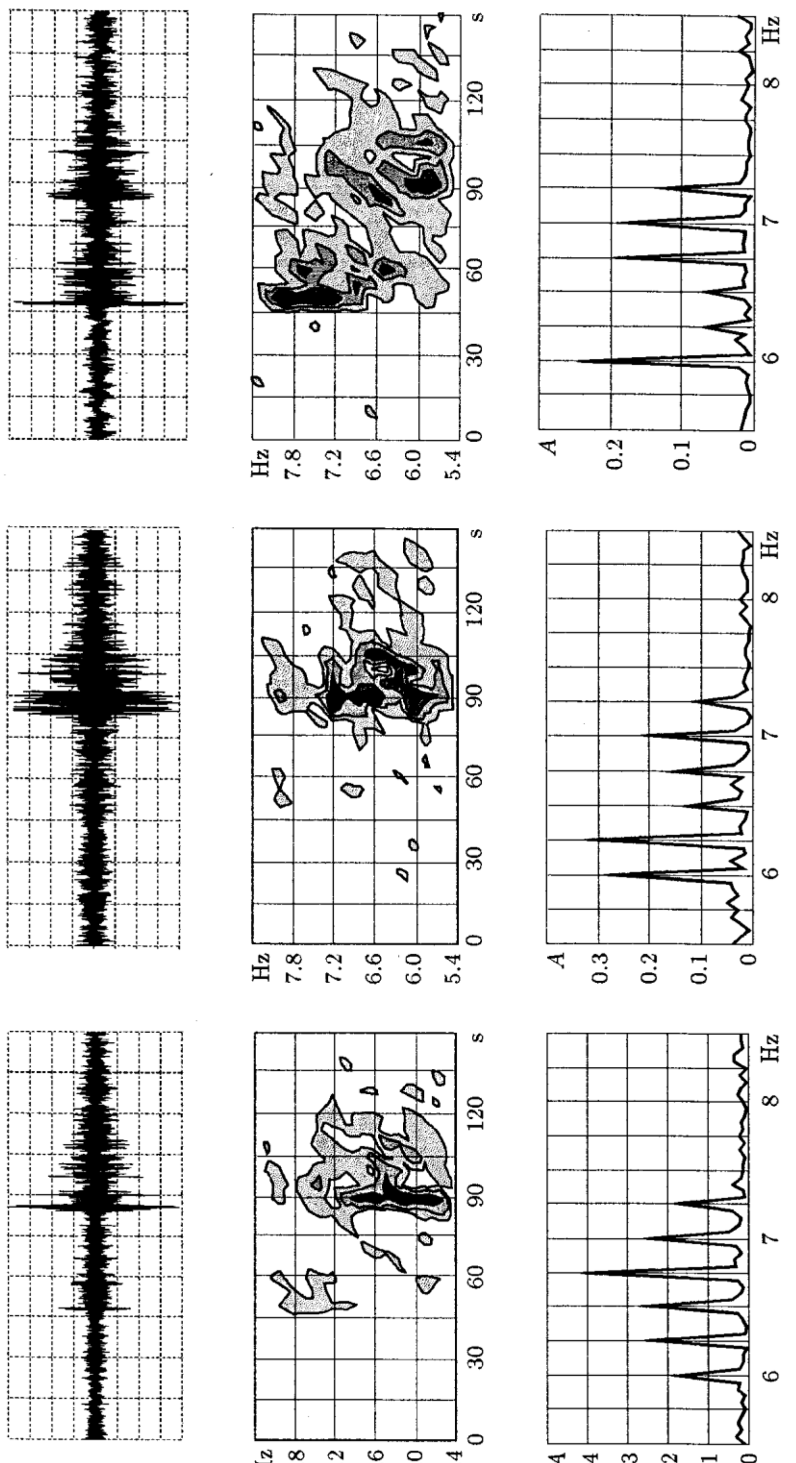

Figure 1

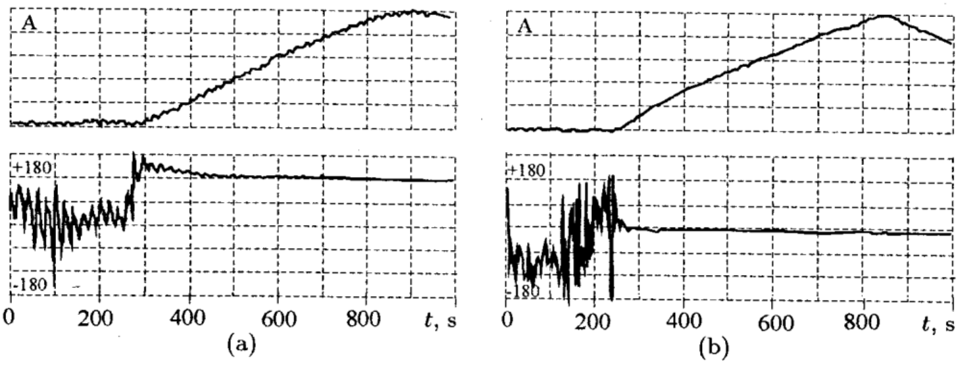

Figure 2. Amplitude and phase of a harmonic signal at quadratic accumulation output: (a) – x component; (b) – z component

calculated by these two measurements bears witness to the existence of one prevailing type of a wave on the trace.

As an example Figure 2 presents amplitude and phase at accumulation output for the frequency 7.25 Hz on the components x and z. The time $t = 200$ s corresponds to switching on of a vibrosource, and $t = 800$ s – to its switching off. Approximately at the 290th second the beginning of an accumulation charge and stabilization of the phase for the component x, and at the 890th second the beginning of the discharge are, respectively, observed. This implies a conclusion about the presence of a dominant wave of the S-type for the given frequency of a harmonic signal and a spatial component of the vibroseismic field. For the component z, the beginning of an accumulation charge and stabilization of a phase at the 250th second, and the beginning of discharge at the 850th second are observed. This bears witness to the presence of a dominant wave of the P-type for the given frequency and the component. The accuracy of defining the travel times is within 5–20% and depends on the signal/noise ratio, which is indicated in the spectra in the bottom part of the figure. The results of measurements are presented in the table.

Travel time of vibroseismic waves

Component	Wave type	Travel time (sec) at frequency (Hz)					
		6.00	6.25	6.50	6.75	7.00	7.25
X	P	—	—	—	—	—	—
	S	83	83	85	90	85	90
Y	P	—	—	—	—	—	—
	S	88	90	88	85	85	80
Z	P	—	63	60	75	48	50
	S	85	90	80	90	—	—

From the data in the table it follows that for the work with the S-type waves it is possible to use the components x and y and any of the six frequencies, as well as the component z at the sounding frequency of 6.00 Hz. For the work with P-waves it is necessary to use only the component z and the frequencies 7.00 Hz, 7.25 Hz. Obviously, the result obtained should be corrected depending on a concrete seismic trace and the type of a vibrational source.

For generalization of the method to large observation bases, where due to attenuation of signals the reception of broadband vibrational seismograms is problematic, it is assumed to use the sounding of a geological structure by a series of monochromatic signals with a frequency step 0.1–0.2 Hz within a concrete frequency range. In this variant of sounding the obtained harmonic seismograms possess a one order higher noise stability in comparison with the broadband vibrational seismograms [6]. By measuring the travel time and the amplitude at the accumulation output for each of the frequencies using the above methods, it is possible to construct synthetic instant spectra similar to the spectra shown in Figure 1. All the presented results and figures are obtained with the help of the computer program V12. Alongside with good possibilities of processing and visualization of the vibroseismic data, the program has a convenient user's interface and can be recommended for a wide circle of users.

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