Optimization problem for Active Geophysical Monitoring Systems.

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***Abstract* —The methods minimization of energy consumption for operation of the system vibrational sounding of Earth (VES) with the given quality are analyzed.**

***Index Terms* — active monitoring, seismic vibrators, minimization of energy, ratio of signal/noise, optimization, resonance coordination, forms of sounding signals, experimental data.**

I. INTRODUCTION

Vibroseismic method for the Earth's sounding (VES) is in most common use in solution of a great number of the geophysical tasks, such as vibroseismic monitoring of seismic_prone zones, seismic tomography, calibration sounding of seismic traces and seismic stations for increasing of accuracy of definition of the coordinates of earthquakes and nuclear explosions etc. [1,2]. The solution of such problems is connected with considerable expenditures of energy (consumption) exceeding 10^6 wt-hours. with sounding at distances greater 1000 km. The minimization of energy (consumption) with the given quality of operation of the system VES is the permanently an actual task. In this paper, the ways of solution of the set problem by methods of optimization of structure and parameters of the system VES are analyzed.

II. PROBLEM STATEMENT

In the generalized form the process of vibrosounding of the Earth can be described by the equation

$$U(x,y,z,t)=\int_0^T K(t,\tau,\bar{x},\bar{y},\bar{z})\,S(t-\tau)\,d\tau+n(t)=v(t)+n(t) \quad (1)$$

here $K(t,\tau,\bar{x},\bar{y},\bar{z})$ is an impulse function of the medium for the coordinates of an radiator and a receiver ($\bar{x},\bar{y},\bar{z}$); $S(t)$ is a sounding signal, $n(t)$ is noise at the recording a point, $v(t)$ is response of the medium as a seismogram as reply to sounding $S(t)$. The quality of measurement of the seismogram parameters of a on against the multiply exceeding noise can be described by the signal / noise as ratio in the form:

$$\gamma^2_{P,S}=\frac{\int_\Omega |v(\omega)|^2_{P,S}\,d\omega}{\int_\Omega N(\omega)\,d\omega} \quad (2)$$

Here the numerator represent the energy of the waves P, S in the sounding frequency band Ω, the denominator represents the energy of noise in the same band. The parameter γ^2 is in a general case, a functional of a number of parameters of the system VES:

$$\gamma^2=\left\{ \mathrm{E}_{P,S},\ \mathrm{r},\ \mathrm{k}(t,\tau,\bar{x}),\ \mathrm{R}_S(\tau),\ \mathrm{R}_n(\tau),\ \mathrm{L}\left[\mathrm{U(t)}\right] \right\}, \quad (3)$$

Here $E_{P,S}$ are energies of the seismic waves P and S at the radiation point; r is the distance, $R_S(\tau), R_n(\tau)$ are parameters of a sounding signal and noise represented as appropriate correlation functions, $L[U(t)]$ is the operator of the processing of recorded signals. In forms of mathematics the problem of optimization is formulated as attaining a certain: γ^{*2} = max γ^2 with. E = const. This means that obtaining the maximum of noise stability of the system VES with constant of consumption energy by the vibrator E.

III. THEORY

In a general case, complexity of the solution of this optimization problem (3) in the closed form is defined by complexity of a medium model. The difficulties of calculation of a wave field (1) in this case are well known. The other simpler ways of solution of this problem consist in the following. A simplified expression for γ^2 can be obtained for a sounding model as a press affecting a quas ihomogeneous halp-space with the force F and the frequency ω_0. For this case, the closed expressions for powers of the seismic waves *P, S, R* have been obtained, over which the above-said complete seismic power at the radiation point is distributed [5]. In view of the above-said it is possible to determine the signal / noise ratio for certain types of waves at recording points. In particular, for the waves P, S we obtain

$$\gamma=A_0 k_{P,S}\, r^n\, \sigma_n^{-1}\, F\, f_0 \sqrt{T}\, \exp(-\alpha\, r) \quad (4)$$

where $k_P=\sqrt{0.0852/\pi\rho V_P^3}$ for the compressional waves, $k_S=\sqrt{0.299/\pi\rho V_S^3}$ for the distortional waves, ρ is the density of the medium under a vibrator, T is duration of sounding, n = -1 for a body wave, $\alpha = 2.5*10^{-4} f_0$ km $^{-1}$, V_P, V_S are velocities of the compressional and the distortional waves in the medium under a vibrator. Based on it numerous data on recording the nuclear explosions [5] and signals of the VES [4] is shown that equation (4) with a required approximation can be used for an evaluation of the characteristics of the system of the VES at distances of recording up to 1000км. For a real medium maximization of functional (3) can be attained at the expense of the following resources:

- *resonance coordination of a vibrator with medium* describedby multilayer model. It makes it possible to rise by one order and more the efficiency of conversion of the energy of consumption to the energy of seismic waves. The experiments with the vibrator CV-100 fully have confirmed such a possibility;
- *consideration of the frequency - dependent properties of the wave propagation medium and microseisms spectra;*
- *optimization of the algorithm of processing L [u (t)];*
- *optimization of a selection of the forms of sounding signals* (with frequency and phase modulation, monochromatic signals).

Let us well on the enumerated possibilities and the ways of their implementation.

The resonance coordination of a vibrator with medium in purpose to raise power of radiated oscillations. It is reached thanks to that the source and the weight of the earth attached to it form oscillatory system, characterised by the resonant frequency. In the field of it escalating of power of radiated oscillations to one order is possible. With the increase of the number of layers of the underlying surface under a vibrator, the curve of radiation power gains a multiresonance character. In particular, for the radiating test site Bystrovka with sequentially increasing thickness of layers H_1=10 m, H_2=150m, H_3=480 m, H_4=2000 m the curve of radiation power of the waves P- N_p depending on frequency has a multiresonance character, represented on fig.1 [7].

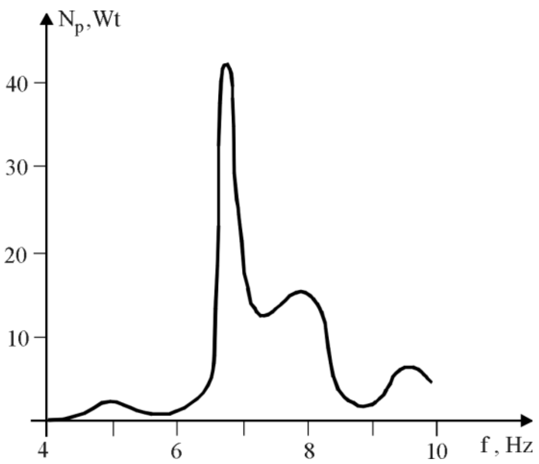

Fig.1. A resonance character power of radiated oscillations..

The account of frequency-dependent properties of medium waves propagation and characteristics microseisms. For the above-mentioned model of a quasihomogeneous half-space, sufficient for obtaining approximate estimations of the frequency characteristic of the medium is described by expression [8]

$$G(w) = \mathrm{A}_0 / r \exp(-\alpha \, \mathrm{r} \, \varpi / 2\pi) \tag{5}$$

The natural seismic noise is characterized by the monotone increase towards of low frequencies. Based on the analysis of the power spectrum of noise in the frequency band 1-20 Hz at a number of seismostation its description as the following expression was obtained:

$$N(w) = D \exp(-\beta \varpi / 2\pi) / (1 + \varpi / 2\pi) \tag{6}$$

Here D is dispersion of noise, β is the coefficient defining steepness of a collapse of the enveloping spectrum of noise, depending on frequency. The experimentally defined value β = 0.025 was used in calculation. The monochromatic signals of the form $S(\mathrm{t}) = \exp(-\eta^2 \mathrm{t}^2)(\cos 2\pi f_0 \mathrm{t})$ were selected as sounding vibroseismic signals in the calculations. With allow once for the given form of signals, the frequency characteristic of the medium *G (ω)*, the spectrum of noise *N*(*ω*), according to (2) the graphics of signal / noise ratio as function of the frequency f and the teleseimic distance Δ was calculated (fig.2).

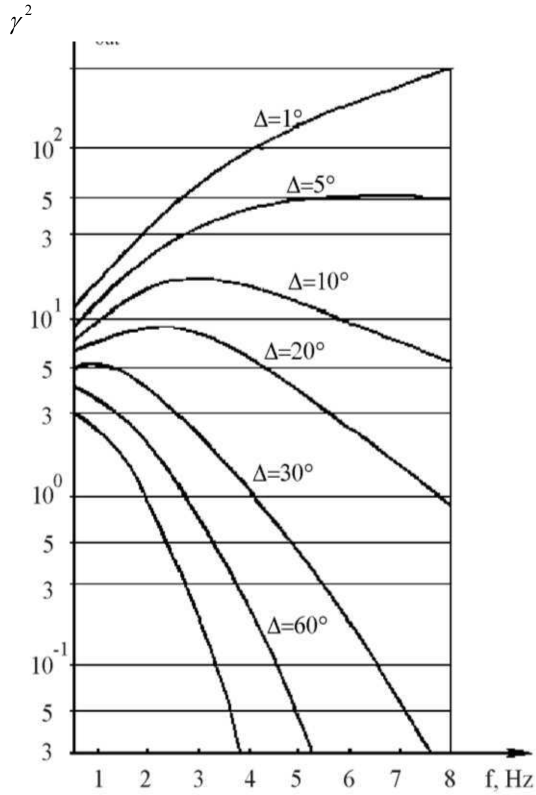

Fig.2

The recommendations on the choice of the optimal range of frequencies of sounding signals with different distances are presented in Table 1:

Table 1

r (km)	100	500	1000	2000	3500	6500-9000
f (Hz)	7.0-8,0	5,0-8,0	2,0-4,0	1,5-2,0	0,5-1,0	0,5

In particular, as follows from the Table, at distances of about 500 km the range of sounding should be selected within 5-8 Hz.

Optimization of the algorithm for processing vibroseismic signals the choice of an operator of processing L [u (t)]. As is known, the main operation in processing vibroseismic of signals is the correlation convolution of a recorded signal with the basic, restored at the recording point according to the law of scanning sounding signal. Some rise of noise stability here can be attained at the expense of introduction of a weighed convolution, taking into account the spectral distinctions of the waves P and S:

$$R(m) = 1/(N - m) \sum_{i=1}^{N-m} a_i u_i S_{i+m} \text{, where } m = 1..., L. \qquad (7)$$

Here $a_i = G_{p,s}(f_i)/D_i$, where $G_{p,s}(f_i)$ a spectrograms of the waves P and S; *Di* is dispersion of noise on the frequency *fi; L* is the number of countings off of show a received signal *u(t)*. As the result of experiments a gain obtained here appears insignificant. In particular, in experiments on sounding at a distance of 355 km a gain in the signal-noise ratio has made about one a half time. [9].

An other reserve of increasing the noise stability is connected with introduction of spatial processing on a set of recording seismometers. As is known, under condition of non-correlatedness of noise between the adjacent seismometers, an expected gain thus being equal to ~ $\sqrt{M}$ in the signal - noise ratio, where M is the number of seismometers. Actually, the gain appears lesser because of differences in the noise levels of between the seismometers..

The further increment of noise stability can be attached by weighed synchronous simulation toting over the set K of identical sessions of sounding [9]. Such an approach is possible due to the high recurrence of the form of signals of VES. The experimentally measured gain at a distance "vibrator - receiver", equal 355 km, with 5-point recording and 21 repeated sessions of sounding has made about 8,5 times.

Optimization of the choice of the forms of sounding signals. The modern vibrators intended for the VES are able to excite in the medium three forms of such signals: monochromatic, signals with frequency modulation (sweep-signals) and phase-manipulating signals. The vibroseismograms restored from such signals against the multiply exceeding noise, have different noise stability estimated by criterion (2). It is theoretically shown and experimentally proved, that for classes of sounding signals $S(t)$ with the correlation function $R_S(\tau)$ criterion (2) will be equal

$$\gamma_C^2 = \frac{E_S \sigma_k^2}{N_0} \int_0^{\infty} \int_0^{\infty} R_k(\tau,\theta) \cdot R_S(\tau) \cdot R_S(0)\, d\tau \cdot d\theta \qquad (7)$$

where $R_k(\tau,\theta)$ is a normalized correlation function of the environment, E_S is the energy of a sounding signal, N_0 is spectral density of noise. From (5) it follows that with the fixed energy E_s, of the highest noise stability (i.e., the maximum γ_C^2 with respect to such a complicated structure of wave propagation as the Earth are the signals with the extended function $R_S(\tau)$. This requirement is met by narrow-band signals, in particular, monochromatic. Based on the results of numerical simulation on evaluating of the criterion γ_C^2 as applied to harmonic, phase-manipulation and sweep-signals, It was shown, that the obtained estimations of noise stability (2) are, approximately, in the ratio 1:0,4: 0,1. In particular, it means, that the noise stability of monochromatic signals is one order higher, than that sweep-signals. Accordingly here there is an additional reserve of increasing the distance of sounding with constant energy consumed by a vibrator. The result obtained at the stage of simulation have been completely confirmed by the results of the experiments, which were carried out at distances of hundreds km [10].

From the analysis of the considered reserves of increasing the noise stability of vibroseismograms it follows that most effective is the resonance method of radiation of vibroseismic signals as monochromatic oscillations. Thus, the gain in power expenses for solution of the various tasks VES can reach two orders. With such a method of sounding it is possible to attain the increased accuracy of measurement of the dynamic characteristics of wave fields, first of all of the parameters of amplitudes and phases of oscillations on a set of point of the space where the units of a reception seismic array place. In particular, in this mode of sounding, high sensitivity of variations of parameters of amplitudes and phases of wave fields in connection with the Earths tides. [11].

CONCLUSION

1. The problem of increasing the sensitivity of the vibroseismic method for the solution of a wide spectrum of the tasks of seismology such, as studying fine geodynamic processes, the calibration of seismic traces and seismostations and etc., is directly connected with the search for effective methods of increasing the noise stability of the system of vibrational sounding of the Earth. In the given paper, the possible ways of rising the noise stability are analyzed. The most effective of them are connected with the resonance coordination of a vibrator with the underlying surface and the choice of monochromatic sounding signals. With such an approach, the increase of efficiency of vibrational sounding of up to two orders is possible with constant consumption energy by a vibrator. This circumstance is especially important when sounding is carried out at distances close to those teleseismic.
2. Thanks to the described power reserves in experiments on vibrating sounding of earth crust in the period solid Earth tide on distances "vibrator-receiver" 350, 430 km accuracy of tidal effects estimation at level 10^{-5}-10^{-6} the first time is reached.

Thus the experimentally obtained estimations of the accuracy of measurements of the vibroseismic oscillations parameters make up 3-5 % in amplitude and (1.5 -2)° in phase.

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