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Optimization Method for Filtering Quasi-Harmonic Disturbances while Preserving the Background Noise for Studying Natural Microseisms

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Abstract—A method is presented for filtering harmonic components of the signal while preserving background broadband noise. The method is widely applied for filtering quasi-harmonic disturbances using the technique of low-frequency seismic sensing (LSS), a useful signal that contains background microseismic noise. The algorithm is based on subtracting the model's harmonic signal from the real signal by selecting the signal parameters, i.e., frequency, phase, and amplitude. To do this, the parameters of the model harmonic signal, at which the energy of the difference signal is minimal, are estimated using the optimization algorithms adapted for the goal function. The proposed method successfully solves the problem of filtering the background microseism noise out of harmonic disturbances.

Key words: microseisms, low-frequency seismic sensing, filtering, optimization, approximation, quasi-harmonic, harmonic, noise, narrow-band, disturbance

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INTRODUCTION

Passive methods for studying the structure of a geological medium based on studying the natural infrasound vibrations of the ground surface are becoming increasingly popular. Among these methods is the technique for low-frequency seismic sensing (LSS) [Rizhov and Birialtsev, 2008], in which low-frequency (1–10 Hz) microseismic vibrations of the ground surface are analyzed in order to study a geological section for the purpose of finding oil and gas deposits. Some characteristics of microseismic vibrations are considered in [Birialtsev and Rizhov, 2008]. The surface sources of vibrations close to the seismic sensor make a significant contribution to the recorded signal, which complicates the analysis of background microseismic vibrations. Characteristic signs of the signal and disturbances are revealed in [Birialtsev et al, 2006]. According to the data of N. K. Kapustyan [2001], technogenic disturbances can be conventionally separated into narrow-band, noiselike, and pulsed. Narrow-band disturbances (NDs) are most often generated by electric machines and low-frequency NDs (units of Hz) are generated by powerful systems, particularly by aggregates of hydroelectric power plants. Higher-frequency vibrations are widely encountered and are generated by pumps and compressors. In the majority of events, the shape of an ND is close to that of a harmonic signal (HS). According to Kapustyan's data [2001], the amplitude of an ND can exceed the level of background natural noise (BNN) by dozens of times, though the relative variations in the amplitude of an ND are less than 10%. These NDs can be considered quasi-harmonic disturbances (QHDs).

The simplest solution for filtering QHD is the rejection of its amplitude by a rejecter filter. As a rule, in the radio technique, the priority of preservation the level of background noise is not important, so rejection is the most widespread method for filtering QHDs and can be implemented based on the element of an analogous instrument [Chastikov, 2001]. In this paper, the problem of filtering QHDs is solved while preserving the shape of level of BNN level.

DESCRIPTION OF THE METHOD

It was shown by Biryaltsev et al [2006] that the correlation of BNN is 1–5 s, while the correlation time of a QHD is much greater than 5 s. The stated problem can be solved using this sign for distinguishing between useful signals and disturbances. The presented filtering method applies the selection of the parameters for a QHD model. A QHD model is presented in the form of an HS with the following parameters: frequency, amplitude, and phase. The parameters of the HS are selected based on the application of the adapted optimization algorithms to the shape of the goal function, which minimize the energy of the resulting signal. Then, the HS is subtracted from the real signal.

Disturbances of a real geophysical signal are nonstationary; hence, in the majority of cases, it is necessary to work with short-time sequences, which are considered to be locally stationary. In addition to the

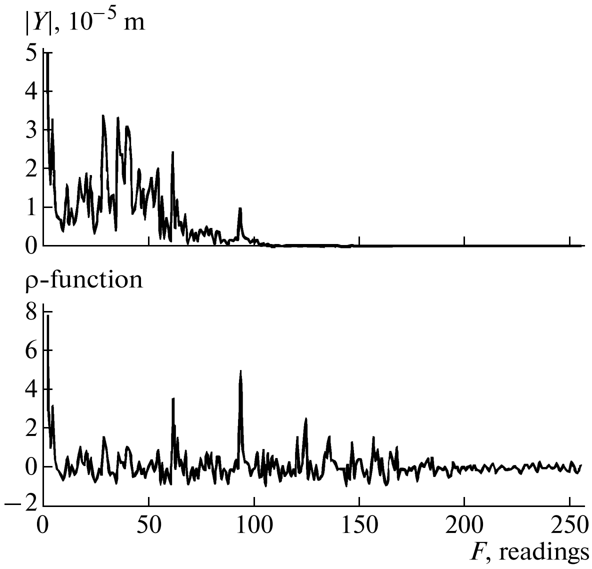

Fig. 1. Example of real amplitude spectrum (top) and its ρ-functions (bottom) with median smoothing window length $N_{win} = 17$.

principal frequency, the Fourier spectrum of a finite discrete harmonic signal contains a series of side lobes (Gibbs effect). To control these lobes, various window functions are used in the spectral analysis, though they do not solve it completely. Thus, a finite harmonic signal in the spectral range is quite complicated. The proposed method is based on the simple subtraction of the model of an HS from the signal to be filtered in a temporal range without using spectral transforms, so the problem of side lobes does not arise.

The proposed method consists of the following blocks:

It is necessary to divide the signal into frames in order to take into account the nonstationary nature of the parameters of a QHD, particularly the amplitude.

Detection. To accurately determine the position of narrow-band components in the spectrum for the step of discretization, the detection procedure described in detail above is performed.

Filtering. The parameters $\hat{F}_{\min}$, $\hat{A}_{\min}$, and $\hat{\Phi}_{\min}$ of the HS model are estimated for each narrow-band component by optimization algorithms adapted to the function of the goal. Then, each model HS is subtracted from the signal to be filtered.

Reconstruction of the signal. To remove the abrupt difference between signals at the frame boundaries, the output signal is reconstructed from each frame using a smoothing window with overlap.

Dividing the signal into frames is used to quantize the nonstationary characteristics of the signal as a whole. Filtering is performed separately for each frame. Selection of the frame size is determined by the following principle conditions:

1) The frame length should be longer than the duration of the wave packages that make up the natural background (1–5 s or 100–500 readings at a discretization frequency of 100 Hz).

2) The frame length should be less than the stationary part of the QHD (10–100 s or 1000–10 000 readings).

As a rule, a frame of 4096 readings is selected. For filtering a less stationary QHD, it is recommended to reduce the frame size to 2048 readings; the frame size is selected as a minimum of 1024 readings.

Detection. The problem of detecting the frequency F_0^i is solved in the block for each significant ND in the spectrum with the number *i*. Analysis of the Fourier spectrum enables us to estimate the frequency of the narrow-band component of the spectrum accurate to the step of discretization. Before calculating the spectrum, the Kaiser window function is applied ($\beta = 2.5$), which insignificantly decreases frequency resolution at sufficient suppression of side lobes.

The spectra under study have a nonuniformly distributed level of background noise, so the they are normalized to the estimate of the background noise through median filtering. The ρ-function, which takes high values of ρ_i in the presence of a narrow peak in the amplitude Fourier-spectrum Y in the reading number *i*, is introduced as follows:

$$\rho_i = \frac{|Y_i| - med(|Y|, N_{win})_i}{med(|Y|, N_{win})_i},$$

where $|Y_i| = \sqrt{\mathrm{Re}(Y_i)^2 + \mathrm{Im}(Y_i)^2}$ is the median smoothing function Y with the window size equal to N_{win}.

The sensitivity of the ρ-function to the width of the spectral peak depends on N_{win}. At $10 < N_{win} < 17$, the function achieves maximal values at the selection of peaks with the width of one reading. An example of a real spectrum and its ρ-function for the window $N_{win} = 17$ is shown in Fig. 1.

At the next step, the distribution of the probability density of the ρ-function is constructed and two hypotheses are raised, i.e., H_0 is the current reading in the spectrum and contains only background noise and H_1 is the current reading of the spectrum and contains a narrow-band disturbance. To determine the statistical dependences of the first type of error α in the detection of an ND, simulation was carried out and the dependences of the probability density *w* and the distribution function *W* on the ratio A_S/A_N were obtained on its basis, where A_N is the mean level of white-noise amplitude and A_S is the amplitude of the principal harmonics of HS in the spectrum.

The results shown in Fig. 2 can be interpreted as follows: the ρ-function enables one to locate the harmonic signal in the Fourier spectrum of the white noise, the amplitude of the principal harmonics A_S exceeds the mean noise level A_N by A_S/A_N times, and a

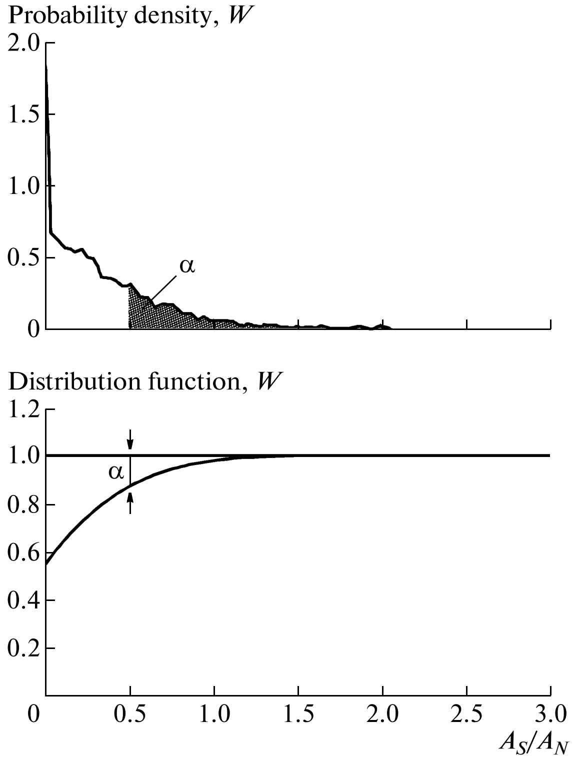

Fig. 2. Probability distribution and probability density distribution of the ρ-function of the white noise spectrum as function of the parameter A_S/A_N.

false response occurs at αercent of the white noise. It seems impossible to estimate the second type of error (missing event) because there are no ideas about the distribution of QHD amplitudes. QHD amplitudes are particularly unique for each geological object being studied and depends on the distance from the source, time of day, and types of technogenic sources. All presented calculation results are obtained for a 4096-reading, long harmonic signal with a discretization frequency of 100 Hz, the energy of which is located at a frequency of 25 Hz (or at the 1024th reading of the spectrum).

Filtering. In this block, the parameters (F, A, Φ) of each QHD are adjusted by optimizing the discrepancy function as follows

$$\varepsilon(F, A, \Phi) = \sum_{T}[X(T) - u(F, A, \Phi, T)]^2,$$

where $u(F, A, \Phi, T)$ is the function of the model HS as shown below:

$$u(F, A, \Phi, T) = A\sin\left(\frac{2\pi F}{N}T + \Phi\right),$$

where N is the signal length and T is the number of reading of the signal.

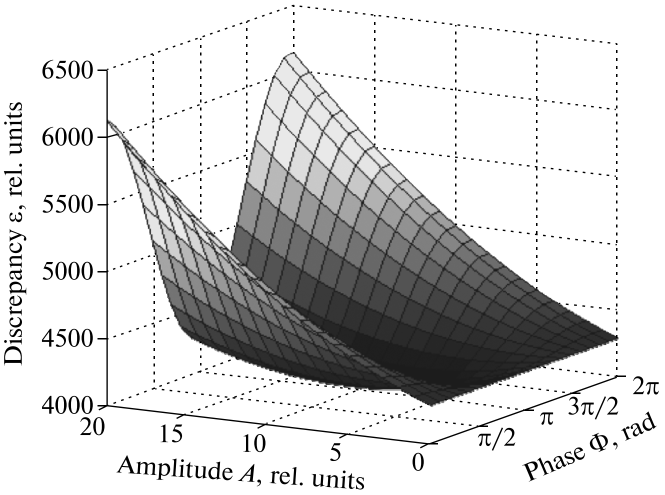

Fig. 3. General view of the goal function at fixed parameter F.

The used parameters F and T are recalculated according to the real frequency $f = F\frac{f_d}{N}$ [Hz] and time $t = T\frac{1}{f_d}$ [s] (f_d is the discretization frequency). Optimization is performed using the adapted algorithms, which take into account the peculiarities of the behavior of the function ε (F, A, Φ), as follows:

– At fixed parameters F and A, the goal function behaves as a one-period sine curve (Fig. 3); hence, in the estimation of its phase, one can approximate the value $\hat{\Phi}_{\min}$, at which it takes the minimum value. Because $\hat{\Phi}_{\min}$ barely depends on A (Fig. 3), any small A ($A = \frac{R(s)}{2}$, where $R(s)$ is the scope of s) can be used. Thus, it can be said that $\hat{\Phi}_{\min}(F)$ is a function that depends on A (when speaking of specific narrow-band disturbance).

– At fixed F and the estimated value of the phase $\hat{\Phi}_{\min}$, the goal function behaves as a parabola (Fig. 3); hence, if the method of square-law approximation is applied, one can estimate $\hat{A}_{\min}$, at which the goal function takes minimum value; i.e., $\hat{A}_{\min}(F) = \hat{A}_{\min}[F, \hat{\Phi}_{\min}(F)]$.

– One can independently estimate $\hat{A}_{\min}$ and $\hat{\Phi}_{\min}$ at any F; therefore, let us rewrite the functional dependence of the goal function in the following form: $\varepsilon(F) = \varepsilon(F, \hat{A}_{\min}, \hat{\Phi}_{\min}) = \varepsilon\{F, \hat{A}_{\min}[F, \hat{\Phi}_{\min}(F)]$. Thus, optimization on three parameters was reduced to optimization on one parameter. When estimating $\hat{F}_{\min}$ of

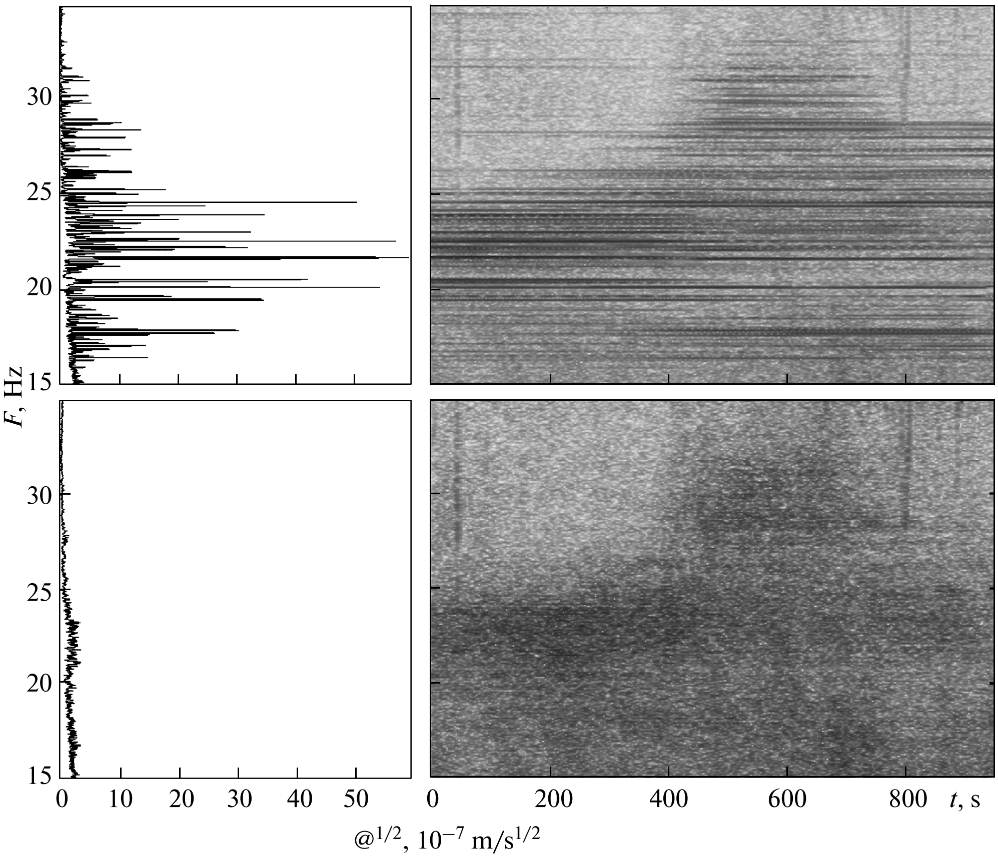

Fig. 4. Example of BNN saturated with ND: a) before filtering, b) result of filtering. On the left cumulative amplitude spectra of the signal, on the right spectrograms (dark color corresponds to high values of the amplitude).

the function $\varepsilon(F)$, the square-law approximation was also applied.

The high accuracy of $\hat{F}_{\min}$ is quite important because the beat effect appears at the summing or subtraction of signals with close frequencies. For example, about 1% of the disturbance remains in the signal with ND at a frequency of 10 Hz at an error in determining the frequency of $\Delta f = 10^{-4}$ Hz. As a rule, two iterations of determining $\hat{F}_{\min}$ are sufficient to obtain parameters with this accuracy. The parameter $\frac{\left|\hat{F}^{\langle k\rangle}_{\min} - \hat{F}^{\langle k-1\rangle}_{\min}\right|}{N/f_d}\Delta f$, where k is the number of the iteration, is taken as a the criterion for deciding whether parameters of the signal are correctly selected.

Reconstruction of the signal. Abrupt differences that distort the initial spectrum appear at the frame boundaries in the reconstruction of the signal due to the nonstationary manner of the parameters of the QHD to be filtered; a Tukey window with the preliminary division of the signal into frames with overlap is applied for their removal. The Tukey window depends on the coefficient $0 \le r \le 1$. If $r = 0$, the window is reduced to a rectangular shape and, if $r = 1$, the window is reduced to a Hamming window [Marpl, 1990].

RESULTS AND DISCUSSION

The spectra and spectrograms of the signal before and after filtering are shown in Fig. 4. When using the proposed method, all well-pronounced QHDs were successfully filtered taking into account the fact that they have nonstationary amplitude characteristics.

The application of classic rejection filtering significantly distorts BNN. For the numerical comparison of the results of the optimization method and rejection filtering, the ratio of the absolute values of the autocorrelation coefficients of noise in the model to the correlation coefficient of the noise in the model and the signal after filtering NDs by two methods in parallel was calculated. Statistical estimates of these parameters in ten experiments are as follows:

1) for the optimization method, $\hat{\mu} = 1.09$, $\hat{\sigma}^2 = 0.32$;

2) for rejection filtering, $\hat{\mu} = 12.99$, $\hat{\sigma}^2 = 13.41$.

This means that BNN is only barely distorted during filtering by the optimization method. Thus, one can say that the use of the optimization method for filtering QHD successfully solves the problem of preserving BNNs for the LSS technique.

In the digital processing of the signals, spectral analysis based on the discrete Fourier transform allows one to achieve a frequency resolution equal to the inverse time of observation. The Pisarenko, MUSIC, and EV parametric methods of harmonic expansion for solving the problem of estimating the frequency of the HS against a background of white noise with high accuracy are known, as well as Berg and Yule-Walker autoregression methods. However, the direct application of these methods to microseismic signals has not yielded desirable results for two reasons:

1) The wideband microseismic background is not white and can exceed the amplitude of the QHD in certain frequency ranges.

2) The estimate of the disturbance frequency is instable to the quantity of singular numbers set before estimation of the frequency parameter. It seems impossible to estimate the amplitude (strong distortions) and the phase of the harmonic disturbance from the spectral estimates by these methods.

The differential-phase method [Khanyan, 2003] for estimating the frequency, phase, and amplitude of the harmonic component of the signal is less accurate than the optimization method proposed by us. For example, at a ratio of the mean level of the white noise spectrum and the amplitude of the additive harmonic noise equal to one, the proposed optimization method for filtering QHD has shown four times more accurate results of frequency estimation.

CONCLUSIONS

A criterion was revealed at the stage of analyzing the nature of anomalies in low-frequency noise that enables one to distinguish them from narrow-band disturbances. This criterion is based on the following. Noise consists of wave packages with random phase durations of 1–5 s, while QHD has a shape similar to HS and a correlation time much greater than 5 s. In this paper, we propose a method for estimating the parameters of the HS model. The method has been achieved fully and is now successfully applied in the LSS technique at the processing stage. The outlook for the development of the method is the possibility of improving it further for filtering complex signals, e.g., QHDs with strongly variable amplitudes inside one frame.

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