Phase-frequency algorithms for resolving complex signals in wave seismic fieldimages

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Abstract. The paper proposes phase-frequency algorithms with equilibrium and non-equilibrium processing based on the pre-developed phase-frequency tracking methods for resolving complex signals in wave seismic field images. It further shows that transition to equilibrium processing enables significant reduction of requirements to apriori information on the properties of useful signals, while non-equilibrium processing increases the resolution of the signals to a great extent. The conducted analytical argument and simulations testified that the algorithms can assure a sufficiently high extraction of signals in their interference zones and harder incoherent noise at propagation of complex signals in dispersive media. The simulation results are justified by real data obtained in processing of seismic wave fields.

1. Introduction

A wide range of tasks in radio detection, navigation, communication and geophysics is complicated byissues related to improper extraction of complex signals, which is primarily conditioned by interference of useful signals, dispersion nature of the signals' propagation medium and the presence of intense incoherent noise [1-3]. Under such conditions, deconvolution (inverse convolution) fails to efficiently detecttemporal positionsof complex signals [4].

Currently, only one component of spectra, which is associated with their amplitude, is commonly used to track seismic wave fields in processing seismic data. In this paper, a linear phase response was additionally introduced. If the conditions are true, deconvolution algorithms allow obtaining reliable estimates of the temporal position of signals; if not, then the algorithms produce significant errors.

Most methods of deconvolution, which are used to compress complex signals and resolve them in wave interference zones, are based on the same principles [1-3]. However, phases of seismic signals contain important information about the location of reflectors, the type of high-speed cutting, absorbing and dispersive properties of layered media [5, 6]. In this respect, much promise is held by phase-frequency methods to track complex signals that are based on the effective processing of the information extracted from phase-frequency characteristics (PFC) of the signals [7-10]. The prerequisite for their successful implementation is the fact that the phase of a signal, in particular the complex law of variation of its PFC, provides for information that allows more efficient detection of the signal and measurement of its temporal positions under high-amplitude noise [7].

2. Phase-frequency algorithms with equilibrium and non-equilibrium processing

Complex signals obtain an important phase-frequency propertythat determines the steady effect of the primary reflection phase spectra and can be used in post review of the proposed phase-frequency algorithms and their applicationsin processing and interpretation of wave field images.Studies have shown that with overlapping reference points and analysis windowcenters, phase spectra of complex signals in an allocated frequency range take on fixed valuesthat are irrelevant of the frequency. This is an important characteristic of the phase spectra of complex signals which is known as the stationary state. Under cut duration of a complex signal, the area of its stationary phase is determined by the following frequency range [11]:

$$\left[\max\left\{0, f_0 - \frac{1}{T}\right\}, f_0 + \frac{1}{T}\right],$$

where f_0 denotes the dominant frequency in the spectrum of the pulse, and T denotes the duration of the analysis window.

The stationary phase of seismic pulses is based on the well-known location principle of signal transmission through linear media. According to this principle, energy can be transferred by a signal only in case of the phase synchronism of its harmonic constituents within the main frequency range. This principle is realized to its fullest extent for perfectly elastic media. Media with absorption demonstrate some deviation from the "ideal" stationary state. However, the analysis of spectra of single reflections in various parts of Western Siberia has shown the possibility of allocation of the stationary phase [10,11]. The stationary areas are allocated for interference oscillations, which are usually recorded under reflection in thin-layered media.

The use of a priori information about the stationary phase spectra of reflected waves allowed constructing phase-frequency algorithms with equilibrium and non-equilibrium processing that does not require apriori information on the frequency response characteristic of the signals. The conversion function of the stated wave field of such algorithms is presented as [12]:

$$L(t) = \sum_{k=1}^{m} w(\omega_k)\cos\left[\varphi(\omega_k, t)\right], \qquad (1)$$

where $w(\omega_k)$ stands for the frequency impulse response, which pattern depends on the realized phase-frequency algorithm; $\varphi(\omega_k,t)$ denotes a current phase spectrum of the image section, which is calculated in a sliding analysis window.

Impulse response $w(\omega_k)$ is set equal to the unit along the whole frequency range for the equilibrium algorithm. On the contrary, $w(\omega_k)$ can be of no particular pattern and be triangular, exponential, or any other pattern for the algorithm with non-equilibrium processing.

In general, expression (1) can be regarded as a result of inverse discrete Fourier transform in application to a digital filter with the following frequency characteristic to the original process [13]:

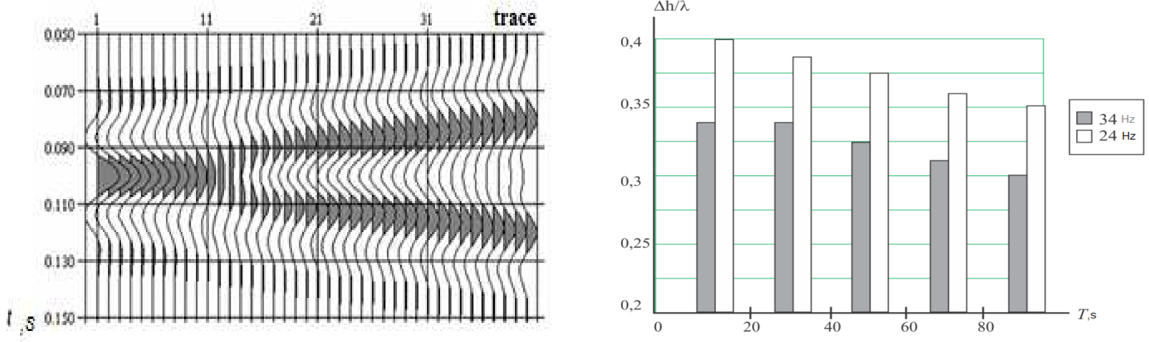
$$H(\omega_k) = \frac{w(\omega_k)}{|X(k)|}, k = \overline{1, m}, \qquad (2)$$

where $|X(k)|$stands for the frequency response characteristic of the signal.

It follows from expression (2) that initially this filter aligns the amplitude spectrum of some test oscillation and then weighs it using some set weight factors. In this case, phase ratios in the source record do not change. It is known [13] that alignment of frequency response character is tics with linear phase-frequency characteristics results in signal compression; thus, a possibility occurs to increase the resolution of the recorded signals. Furthermore, frequency characteristics of the filter can be controlled during implementation by setting weight factors $w(\omega_k)$; thus, the high frequency components of the signal can be amplified or attenuated.

3. Modeling results

The proposed algorithms were studied based on computer simulation using the *Geoseif*algorithmic software system [9]. A synthetic wave field with two identical waveforms (Figure 1, a) was used to study the resolution of the non-equilibrium algorithm. A triangular function was used as weight, and a bell-shaped wavelet had the central frequencies of 24 and 34 Hz. The non-equilibrium algorithm shows a resolution of the order of ¼ of the wavelength in the vertical dimension (Figure 1, b), and is thus applicable to data distorted by interference.



a

b

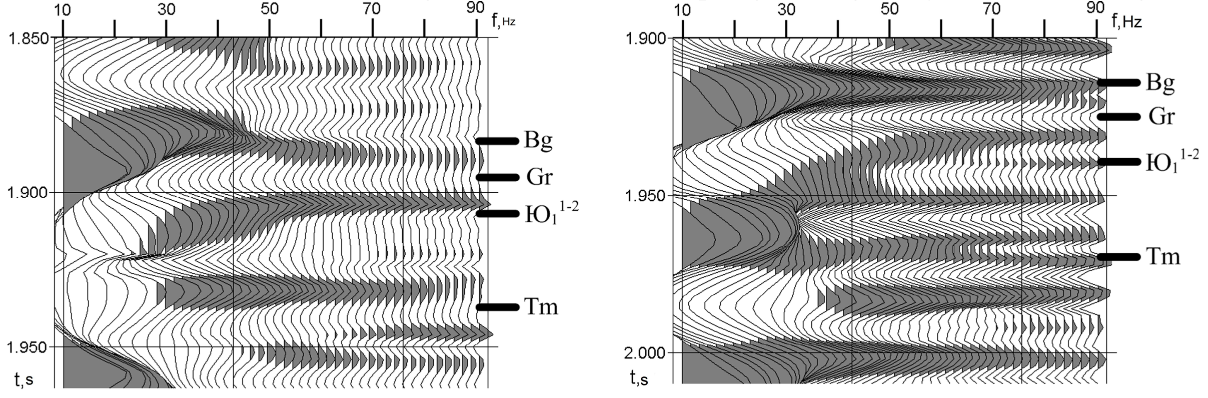
Figure 1. Resolution of the non-equilibrium phase-frequency algorithm: a – synthetic seismogram; b – respective vertical resolution (*Δh*), *λ* – the wavelength.

4. Processing and interpretation of seismic wave fields

The proposed algorithms were used to predict the types of geological sections in near-wellbore and inter-well spaces under the conditions of thin-layer structures when strong reflection interference was observed in the images of seismic fields. At that, a set of conversion functions of a common pattern was formed for each analyzed seismic trace in the investigated strata:

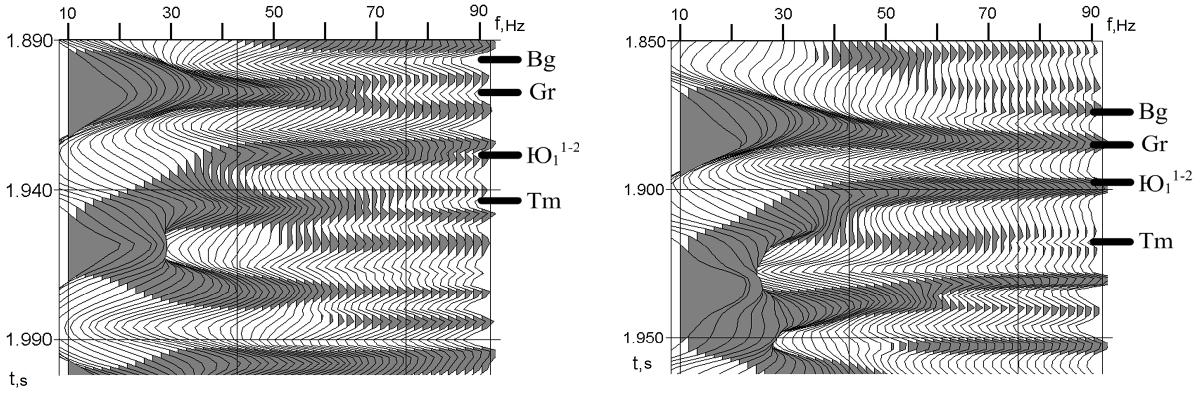
$$L_i(\tau) = \sum_{k=0}^{n-1} W_i(f_k)\cos\left(\varphi(f_k) - 2\pi f_k \tau\right)$$

Figure 2 presents reference FAN-images of geological sections of four types allocated according to geo-physical well logging data at an oil field in the Ob river area of Tomsk oblast. These FAN-images were used to determine the propagation area of the geological section types in the field. The prediction was delivered with a classification algorithm based on the topological singularity of the FAN-images.



I – type

II – type



III – type IV – type

Figure 2. Reference FAN-images allocated for different types of geological sections. Gr – Georgiev suite, Tm – Tyumen suite.

The plotting results of the geological sections of the field obtained with the phase-frequency algorithms were later confirmed during drilling exploratory and production wells.

5. Conclusion

Studies based on simulated and real data demonstrated that the proposed phase-frequency algorithms with equilibrium and non-equilibrium processing could be successfully used to increase the resolution of signals in wave field images. Moreover, the algorithms require a priori information only about the values of the phase-frequency response of the recorded signals.

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