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Trace-transform-based time-frequency filtering for seismic signal enhancement in Northeast China

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ABSTRACT

In this paper, a trace-transform-based radial trace time frequency peak-filtering method (RT-TFPF) with temporal-spatial directions is proposed. It utilizes the similarity of data along the reflection event and computes the temporal–spatial radial directions by seeking the local maximum value of a constructed trace function. This method takes advantage of the TFPF in non-stationary signal estimation, especially with no prior knowledge. Furthermore, applying the filtering in the temporal–spatial domain results in less biased TFPF estimation. Within the framework of the trace transform, the specified trace function first calculates the centroid and then accumulates the energy of the reflected signal along the trajectory, helping to find the locally optimal filtering directions automatically. Experiments on both synthetic record and field data in North-East China demonstrates good performance–strong random noise can be attenuated, while at the same time, the estimated reflection signal is more accurate for use in interpretation.

1. Introduction

In seismic exploration, random noise has various causes, not only during data acquisition, but also during various procedures in data processing such as deconvolution, migration, or even filtering. In Northeast China, countermeasures are hard to apply due to the complex geology (which leads to complicated coherent noise), and to severe winter storms for more than 5 months a year (which leads primarily to powerful random noise). Therefore, many available methods (Deng et al., 2010, 2011; Naghizadeh and Sacchi, 2009; Satish and Nazneen, 2003) do not produce satisfactory results. Time-frequency peak filtering (TFPF) and its extension in the temporal and spatial domain would be a good choice (Lin et al., 2007) to eliminate the strong random noise.

The conventional TFPF algorithm proposed by B. Boashash and M. Mesbah has found its application in seismic record denoising and achieved some good results in the Daqing oil basin in Northeast China, because of its advantages in non-stationary signal estimation without prior knowledge, even under low signal-to-noise ratio (SNR) (Lin et al., 2007, 2008; Liu et al., 2013). To achieve better performance, in the past 2 years, Wu et al. have analyzed the bias condition of conventional TFPF and developed the radial-trace TFPF (RT-TFPF) by utilizing the correlation between adjacent seismic channels (Wu et al., 2011). The RT-TFPF can stretch the valid signal (Henley, 2001) to make it as linear as possible within the window, so that the unbiased condition is better satisfied and a more satisfactory result could be obtained for both noise suppression and signal enhancement.

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In RT-TFPF, the most crucial factor is to find the radial trace direction along which the linearity of the effective signals is most enhanced. To begin, a cluster of parallel radial traces with a fixed angle of 45 degree are used because no interpolation needs to be involved and all the effective signals could be stretched, although not to the greater extent. Then other angles of radial traces, parabolic traces (Tian and Li, 2014) and hyperbolic traces (Tian et al., 2014) are constructed to find the direction that approximately aligns with the reflection event according to its time-distance curve equation. In this paper, we propose a temporally and spatially varied radial trace TFPF based on a new trace transform to improve the performance of the above RT-TFPF and deal with seismic trace ensembles including, but not limited to, CMP trace ensembles.

The rest of this paper is organized as follows. In section II, we present the principle of the conventional TFPF and derive the bias reduction condition with the help of a trace transform, and then we illustrate, using a synthetic model, both advantages and disadvantages of the 2D TFPF idea. Section III develops a trace functional to keep track of the temporally and spatially varied seismic event and derives the corresponding trace-transform-based 2D TFPF strategy, which is then applied to both a synthetic record and field data from Northeast China in Section IV. Finally, we present our conclusions in Section V.

2. The filter methodology

2.1. Conventional time-frequency peak filtering

TFPF has been proved to successfully reconstruct the reflected signals from observations corrupted by additive random noise (Lin et al., 2007). It may be divided into two steps, where the first consists in encoding the noised signal as the instantaneous frequency (IF) of a frequency-modulated analytic one, and the second in recovering the desired signal by IF estimation of the analytic one (Boashash and Mesbah, 2004).

The above two procedures can be expressed as follows:

$$z_s(t) = e^{j2\pi\mu\int_0^t s(\lambda)d\lambda} \tag{1}$$

$$\hat{x}(t) = \hat{f}_{z_s}(t) = \mu^{-1}\underset{f}{\text{argmax}}\ [PW_{z_s}(t,f)] \tag{2}$$

where $z_s(t)$ is the frequency-modulated analytic signal of the random noised signal $s(t)$ with scaling parameter μ, $PW_{z_s}(t,f)$ is the pseudo Wigner–Ville distribution (PWVD), and $\hat{x}(t)$ is the reconstructed signal, which is equal to IF $\hat{f}_{z_s}(t)$. For the special case where the desired seismic signal is linear in time, e.g., $x(t) = \alpha t + C$, where α and C are constants, the bias $B(t)$ of TFPF can be written as:

$$B(t) = \underset{f}{\text{argmax}}\left(\frac{4\pi^2 k_{n2}\mu^2}{(2\pi^2 k_{n2}\mu^2)^2 + (2\pi f - 2\pi\mu x(t))^2}\right) \cdot \frac{1}{\mu} - x(t) = 0 \tag{3}$$

where k_{n2} is the second cumulant of the noise.

This means that, if the desired signal is linear (or we can say low frequency), conventional TFPF would give an unbiased estimation of the pure signal. For example, for seismic signals whose dominant frequencies are around 20 Hz, TFPF could recover the effective signal with almost no distortion of the amplitudes. However, for intermediate frequency (around 40 Hz) seismic record discrimination, conventional TFPF would cause serious amplitude attenuation, even for the shortest window in PWVD (Wu et al., 2014). In other words, sometimes there is no guarantee of linearity (Yu et al., 2015) of the desired signal, even for extreme values of the parameter. The limitation of the conventional TFPF is that it views the signal only along the time direction where the rapid variation may cause serious distortion. Furthermore, the correlation (Jiang et al., 2014) between adjacent channels is not considered and utilized in conventional TFPF.

2.2. Parallel radial trace TFPF based on radial trace transform

To take advantage of the amplitude correlation within a 2D seismic record, a linear trace transform is a good choice. One type of linear trace transform does not calculate any functional, but only extracts the amplitudes from the 2D trace ensemble and then interpolates them onto another 2D panel. This is also known as the radial trace transform (Li et al., 2013). Though only a point-to-point mapping, the radial trace transform can greatly reduce the frequency of a signal whose wavefront aligns with the transform trajectories.

The reduced-frequency signal is useful for TFPF because the unbiased estimation is based on the premise that the desired signal is linear in time (approaches DC). Therefore, if the direction of the trajectories could be selected to increase the linearity (or decrease the frequency) as much as possible, the 2D TFPF that filters the record along the trajectories would provide a much better performance than the conventional TFPF.

For 2D TFPF, the first step is to transform the original noisy record $u(x,t)$ into the radial trace transform domain $u'(v,t')$, i.e.:

$$u'(v,t') = RT(x,t) \tag{4}$$

where t and t' share the same scale and the same sample interval.

The second step is to find the optimal direction v_i along which the dominant frequency is highly reduced and encode $u'(v_i,t')$ as the IF of a frequency-modulated analytic signal,

$$z_{v_i}(t') = e^{j2\pi\mu\int_0^t u'(v_i,t')dt'} \tag{5}$$

The next step consists in estimating the spatiotemporal signal in the R–T domain with the TFPF algorithm

$$\hat{u}(v_i,t') = \hat{f}_{z_{v_i}}(t') = \frac{\arg\ \max_f [W_{z_{v_i}}(t',f)]}{\mu} \tag{6}$$

and finally with the inverse transform, we obtain the noise-free seismic signal in the X–T domain

$$\hat{u}(x,t) = RT^{-1}\{\hat{u}(v_i,t')\} \tag{7}$$

2D TFPF filters a record with the help of the radial trace transform to better satisfy the condition of equation (3),