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A novel nonstationary deconvolution method based on spectral modeling and variable-step sampling hyperbolic smoothing

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ABSTRACT

Deconvolution is an important part of seismic processing tool for improving the resolution. One of the key assumptions made in most deconvolutional methods is that the seismic data is stationary. However, due to the anelastic absorption, the seismic data is usually nonstationary. In this paper, a novel nonstationary deconvolution approach is proposed based on spectral modeling and variable-step sampling (VSS) hyperbolic smoothing. To facilitate our method, firstly, we apply the Gabor transform to perform a time-frequency decomposition of the nonstationary seismic trace. Secondly, we estimate the source wavelet amplitude spectrum by spectral modeling. Thirdly, smoothing the Gabor magnitude spectrum of seismic data along hyperbolic paths with VSS can obtain the magnitude of the attenuation function, and can also eliminate the effect of source wavelet. Fourthly, by assuming that the source wavelet and attenuation function are minimum phase, their phases can be determined by Hilbert transform. Finally, the estimated two factors are removed by dividing them into the Gabor spectrum of the trace to estimate the Gabor spectrum of the reflectivity. An inverse Gabor transform gives the time-domain reflectivity estimate. Tests on synthetic and field data show that the presented method is an effective tool that not only has the advantages of stationary deconvolution, but also can compensate for the energy absorption, without knowing or estimating the quality factor Q.

1. Introduction

As seismic techniques move more from exploration to hydrocarbon development and production, the need for high-resolution seismic data becomes more acute (Jia et al., 2004). Deconvolution has been an essential tool for the construction of high-resolution seismic images. Most conventional deconvolution methods, like Wiener or predictive deconvolution, are based on a simple model that the wavelet does not change with traveltime. Actually, when seismic waves propagate through the earth subsurface, the absorption and dispersion effects will cause attenuation of wave amplitudes and shape distortion of seismic waveforms. Therefore, seismic data is nonstationary.

The nonstationarity of seismograms is addressed by many authors, whose studies generally fall into two distinct categories, depending on whether the quality factor (Q) is required or not. One category is inverse Q filtering which requires prior knowledge of Q, the other is nonstationary deconvolution without knowing Q.

For the first category, Hale (1981, 1982) found that the inverse Q filtering overcompensated the amplitudes for the later events in a seismic trace. In order to obtain reasonable amplitude, he proposed Q adaptive deconvolution algorithm, but the result was not desired. Hargreaves and Calvert (1991) pointed out that Robinson's (1979) frequency-domain rescaling and interpolation method was analogous to the Stolt (1978) migration algorithm, and developed an inverse Q filtering approach. According to the model presented by Kjartansson (1979), Pei and He (1994) derived an inverse Q filtering method, which could compensate the amplitude and correct the phase distortion, but it is applicable only to the data with high signal-to-noise (SNR). Wang (2002, 2004, 2006) presented a stable inverse Q filtering method for constant interval Q models with variable Q values, which could effectively and stably compensate for both amplitude and phase. Zhang and Ulrych (2007) introduced the least squares approach and Bayesian theory into the inverse Q filtering and obtained good results. Wang et al. (2008) developed an inverse Q filtering in time domain to improve calculation efficiency. Yan and Liu (2009) extended a stable and effective poststack inverse Q filtering to the prestack data. Wang (2011) developed a new attenuation compensation method based on inversion theory. The common drawback of these methods is that they need to know Q accurately. Therefore, these methods have some limitations in practical applications because Q estimation is challenging in field data.

For the second category, Clarke (1968) proposed a nonstationary convolutional model based on optimal Wiener filtering. Griffiths et al.

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(1977) developed a time-adaptive prediction filtering that was effective in removing multiples. Koehler and Taner (1985) introduced a general mathematical theory of time-varying deconvolution, and showed it to be equivalent to a multi-channel process. Unlike the stationary model of a seismic trace, Margrave (1998) presented a nonstationary convolution model which addressed the earth attenuation. Then Margrave and Lamoureux (2001) developed a nonstationary deconvolution using Gabor transform. Margrave et al. (2004) presented a nonstationary deconvolution technique, called hyperbolic smoothing, to suppress the amplitude equalization effect. Montana and Margrave (2005) improved the performance of Gabor deconvolution by phase correction. Margrave et al. (2011) introduced the Gabor transform, based on a complete set of windows, and developed a Gabor-domain deconvolution algorithm by a spectral smoothing technique.

In this paper, we propose a nonstationary deconvolution algorithm based on spectral modeling (Rosa and Ulrych, 1991) and variable-step sampling (VSS) hyperbolic smoothing. Unlike the conventional hyperbolic smoothing method, we estimate the source wavelet by spectral modeling at first, and then smoothing the Gabor magnitude spectrum of seismic data along hyperbolic paths with VSS can obtain the magnitude of the attenuation function, and can also eliminate the effect of source wavelet. Finally, we applied our new method to both synthetic and real data.

2. Method and theory

2.1. Gabor transform

The forward Gabor transform of a time-domain signal $s(t)$ is defined as (Gabor, 1946)

$$S_g(\tau,f)=\int_{-\infty}^{+\infty} s(t)g(t-\tau)e^{-2\pi i f t}dt, \tag{1}$$

where $g(t)$ is the Gabor analysis window and τ is the location of the window center. Given $S_g(\tau, f)$, the signal can be reconstructed to form the expression

$$s(t)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} S_g(\tau,f)\gamma(t-\tau)e^{i2\pi f t}dfd\tau, \tag{2}$$

where $\gamma(t)$ is the Gabor synthesis window. The analysis and synthesis windows must satisfy the condition

$$\int_{-\infty}^{+\infty} g(t)\gamma(t)dt=1. \tag{3}$$

To simplify, let $\gamma(t) = 1$. That is, it is possible to choose a set of Gaussians such that

$$\sum_{k\in z} g(t-k\Delta\tau)\approx 1, \tag{4}$$

where

$$g(t-k\Delta\tau)=\frac{\Delta\tau}{T\sqrt{\pi}}e^{-[t-k\Delta\tau]^2T^{-2}}, \tag{5}$$

with T being the Gaussian half width and $\Delta\tau$ being the spacing between Gaussians.

2.2. Nonstationary convolutional model

The stationary theory is based on a stationary convolutional model of a seismic trace that is often written

$$s(t)=w(t)*r(t)\equiv\int_{-\infty}^{\infty} w(\tau)r(t-\tau)d\tau, \tag{6}$$

where $w(t)$ is the seismic wavelet and $r(t)$ is the reflectivity.

From the Eq. (6) above, the seismic wavelet does not evolve with time. This means that the wavelet is stationary. Actually, when seismic waves propagate through the earth subsurface, the absorption of the medium will cause attenuation of the wave amplitudes and shape distortion.

Margrave (1998) presented a trace model that included the source waveform and the nonstationary effects of dissipation as predicted by the constant-Q model (Futterman, 1962). Firstly, the effect of constant Q can be modeled as

$$s_Q(t)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \alpha_Q(\tau,f)r(\tau)e^{2\pi i f[t-\tau]}d\tau df, \tag{7}$$

where $r(\tau)$ is the reflectivity and the constant-Q attenuation function is

$$\alpha_Q(\tau,f)=e^{{-\pi f\tau}/{Q}+iH\left({\pi f\tau}/{Q}\right)}, \tag{8}$$

where H denotes the Hilbert transform. Eq. (7) can be understood as a nonstationary convolution by noting that the f integral can be written as

$$a_Q(\tau,t-\tau)=\int_{-\infty}^{\infty} \alpha_Q(\tau,f)e^{2\pi i f[t-\tau]}df, \tag{9}$$

so that

$$s_Q(t)=\int_{-\infty}^{\infty} a_Q(\tau,t-\tau)r(\tau)d\tau. \tag{10}$$

As defined by Eq. (7), s_Q models dissipation for an impulsive source. For a more general source, we simply apply it with a stationary convolution and write our final nonstationary trace model as

$$S(f)=W(f)\int_{-\infty}^{\infty} \alpha_Q(\tau,f)r(\tau)e^{-2\pi i f\tau}d\tau, \tag{11}$$

where W and S are the Fourier transforms of the source and the nonstationary seismic trace respectively.

Finally, Margrave et al. (2004) applied the Gabor transform in Eq. (11) and derived an asymptotic result as

$$S_g(t,f)\approx W(f)\alpha_Q(t,f)R_g(t,f). \tag{12}$$

As shown above, $S_g(t,f)$ and $R_g(t,f)$ are the Gabor transform of nonstationary trace and the Gabor transform of the reflectivity separately.

2.3. Gabor deconvolution algorithm

As in stationary deconvolution, one of the main steps is wavelet estimation from the seismic data. The accuracy of the wavelet is directly related to the accuracy of the deconvolution. In nonstationary convolutional model, nonstationary wavelet is composed of source wavelet and attenuation function.