Journal of Applied Geophysics 90 (2013) 92–95

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A novel seismic wavelet estimation method

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ARTICLE INFO

Article history:
Received 11 July 2012
Accepted 15 January 2013
Available online 24 January 2013

Keywords:
Seismic data
S Transform
FFT
LS method
Seismic wavelet estimation

ABSTRACT

A novel seismic wavelet estimation scheme is proposed based on S transform and Least Squares (LS) method. The scheme can reconstruct the coherent components after estimating major wavelet even when the signal-to-noise ratio (SNR) is low. The main frequency and delay along the event should be estimated. The proposed scheme can estimate seismic source wavelet with minor distortion. It can be realized as follows: firstly uses an S transform to estimate the delay and coarse frequency information, secondly applies a filter designed in S transform domain, thirdly gets the data in time domain by applying an inverse S transform to the filtered data, fourthly uses a windowed FFT unit to get the accuracy frequency estimation, and fifthly reconstructs the seismic source wavelet after estimating the energy based on LS method in time domain. Furthermore, the space–time-variant characteristic of the source wavelet is taken into account. An iteration scheme is designed to estimate all components of wavelet. The simulation results show that the proposed method can estimate the source wavelet effectively when the SNR is higher than 0 dB.

1. Introduction

With the increase of the geophysical exploration complexity and depth, the power of useful seismic data is decreased and the random noise increases. The useful seismic data is usually drowned in the random noise. To meet the demand of seismic imaging, effective random noise suppression method is needed to improve the signal-to-noise ratio (SNR) of seismic data while the primary features of the data unchanged. Noise suppression in transform domain is a basic method: seismic data is converted into a transform domain, and then denoised by threshold in the transformed domain, finally inversed into the original domain. The usual transform methods include frequency-spatial (f-k) method based on Fourier-transform (Canales, 1984), τ–p technique based on Radon transform (Kappus et al., 1990), Wavelet transform (Zhang and Ulrych, 2003) and Curvelet transform (Neelamani et al., 2008; Tang and Ma, 2011). There is no method can suppress all kinds of noise. The kind of method is chosen dependent on the noise type. For example, f-k method and τ–p are usually used to reduce coherent noise. Researchers often choose the wavelet and Curvelet transforms to shrink random noise. The noise suppression is always done by filtering. Several adaptive filters which were applied in reducing random noise in seismic data are compared by Ristau and Moon (2001). Prediction-error filters are proposed for coherent noise attenuation by Guitton (2002). A new filtering technique for random and coherent noise attenuation by applying empirical mode decomposition is shown by Bekara and Baan (2009).

In order to improve the seismic resolution, the source wavelet estimation is also needed. The methods mainly divided into two kinds: one is deterministic wavelet extraction method, and the other is statistical wavelet extraction method. The deterministic wavelet methods include wiener filter method (Leinbach, 1995), linear inversion method (Cooke and Schneider, 1983), Bayesian estimation method (Buland and More, 2003) and so on. The statistical methods include higher order statistics method (Zhang and Zhang, 1994), subspace method (Moulines, 1995) and so on. The paper focuses on the deterministic wavelet estimation at low SNR and takes the space–time-variant characteristic of the source wavelet into account.

2. Proposed seismic data processing method

The scheme shown in Fig. 1 is proposed for seismic source wavelet estimation based on S transform and LS methods.

Major steps are given as follows: firstly apply an S transform on the seismic data to estimate the parameters such as delay and frequency information; then design a filter according to the estimation and apply an inverse S transform to the filtered signals; and reconstruct the source wavelet based on LS method with some assumption of seismic wavelet after the accurate main frequency estimation done in Fourier frequency domain. The phase assumption of seismic wavelet includes mixed phase, minimum phase and Ricker (zero phase) wavelet. According to Dey (1999), the major wavelets in the real

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http://dx.doi.org/10.1016/j.jappgeo.2013.01.007

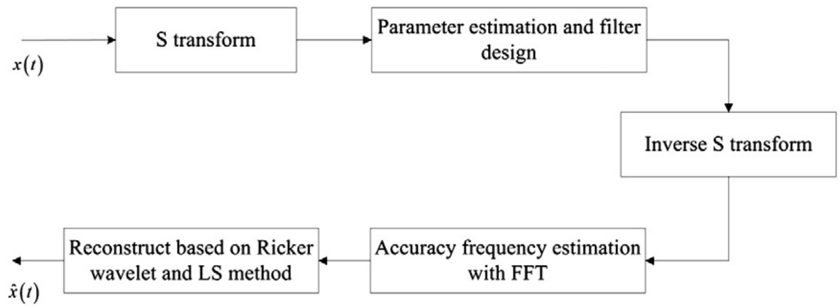

Fig. 1. Proposed wavelet estimation scheme.

seismic data can be represented by zero-phase Ricker wavelets. The author pointed out that the simulation result is close to measured result using zero-phase Ricker.

The zero-phase Ricker wavelet can be expressed as:

$$R(t) = \left(1-2\pi^2 f_m^2 (t-\tau)^2\right) e^{-\pi^2 f_m^2 (t-\tau)^2} \tag{1}$$

where f_m is the main frequency, and τ is the delay of arrival.

The scheme is analyzed based on this assumption. However, it can be extended to process other assumptions of the seismic wavelet.

The S transform produces a time frequency representation of a time series. It can be derived from short time Fourier or wavelet transform, and has some unique advantages: its time–frequency resolution is related to frequency resolution and can be treated as a special case of the Fourier Transform with the characteristic of multiresolution. According to Liu et al. (2011), the S transform of a function $h(t)$ can be defined as a wavelet transform with a specific mother wavelet multiplied by a phase factor:

$$S(\tau,f) = \int_{-\infty}^{\infty} h(t) w(t-\tau,f) dt \tag{2}$$

where $w(t,f)$ is the mother wavelet and defined as:

$$w(t,f) = \frac{|f|}{\sqrt{2\pi}} e^{-\frac{f^2 t^2}{2}} e^{-j2\pi ft}. \tag{3}$$

We should note that the basic wavelet of S transform doesn't have to meet the admissibility condition.

2.1. Single wavelet estimation method

We can reconstruct the seismic wavelet accurately and quickly as follows:

1. Apply an S transform to the seismic data;
2. Get the position of the maximum amplitude in S transform domain as the delay estimation $\hat{\tau}_1$ and the coarse main frequency estimation $\hat{f}_{s1}$;
3. Design a filter in the S transform domain with the center point is $(\hat{\tau}_1, \hat{f}_{s1})$;
4. Apply an inverse S transform to the filtered data which is the output of step 3 and get the data in time domain;
5. Apply FFT to the time domain data;
6. Search the maximum value of the output, and make record of the position as the accurate main frequency estimation $\hat{f}$;
7. Reconstruct the Ricker wavelet according to Eq. (1) as:

$$\hat{R}_1(n) = \hat{A}\left(1-2\pi^2 \hat{f}^2 (nT_s-\tau)^2\right) e^{-\pi^2 \hat{f}^2 (nT_s-\tau)^2} \tag{4}$$

8. Estimate the amplitude of the seismic wavelet:

$$\hat{A} = \arg\min_{A} \left(\sum_{n=0}^{N-1} \left| R(n) - \hat{R}_1(n) \right|^2 \right). \tag{5}$$

2.2. Multi-component

Taking the source wavelet space–time-variant into account, the seismic data can be expressed as $x(t)$ which includes multi-component Ricker wavelet and noise:

$$x(t) = r(t) + w(t) = \sum_{k=0}^{K-1} a_k \left(1-2\pi^2 f_k^2 (t-\tau_k)^2\right) e^{-\pi^2 f_k^2 (t-\tau_k)^2} + w(t) \tag{6}$$

where K is the component number, a_k is the component amplitude, $w(t)$ is a complex Gaussian noise with mean zero and variance σ_n^2.

In this letter, we proposed a signal separation method to suppress stronger component in Fig. 2. The main idea is: firstly, estimate the parameters of stronger component according to their amplitude based on the method mentioned in Part A; secondly, eliminate the other signals from the data with a window in time domain according to the delay estimation; and thirdly, estimate other components by iterating the process to improve the reliability.

The threshold is selected according to Eq. (7):

$$\theta = \max\{abs(\bar{s} + 2\bar{\sigma}_s), abs(\bar{s} - 2\bar{\sigma}_s)\} \tag{7}$$

where $\bar{s} = E(ST(R(n)))$ is the mean value of seismic data in the S transform domain, $\bar{\sigma}_s = \mathrm{var}(ST(R(n)))$ is the variance value of the seismic data in the S transform domain.

2.3. Measure of performance

The seismic signals can be divided into two parts: useful signal and noise. SNR is a standard to measure the quality of data processing. However, it cannot measure the signal distortion. In this letter, we introduce the mean square error (MSE) to measure the distortion between the original source wavelet and the reconstructed wavelet. If the reconstruction can be done without distortion, the estimated wavelet will be equal to the original source wavelet.

$$MSE = \frac{\sum_{n=0}^{N-1} \left(\hat{S}(n) - S(n)\right)^2}{N} \tag{8}$$

where $\hat{S}(n)$ and $S(n)$ denote the reconstructed and ideal data respectively, N is the number for processing.