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Spectral decomposition with space-varying extracted seismic wavelets

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Summary

In seismic interpretation, spectral decomposition has been effectively used in many applications, such as channel delineation, gas reservoir detection and thin-bed interpretation. There are different methods to do spectral decomposition, but they are using one or more mathematical functions (such as Morlet wavelet) as the basis to convolve with seismic sampling data. Very often the mathematical functions used deviate substantially from the actual seismic response underground. This causes the popular ringing effect in spectral decomposition results and could interfere with, or even worse lead to false interpretation. The author proposed (Zhang, 2013) a method that used the extracted seismic wavelet to replace the mathematic functions to do spectral decomposition. The result from that method showed much less ringing effect and therefore less ambiguity for interpretation. However, a single extracted wavelet was used in that method and it works well if the actual wavelet doesn't change much. To address issues when the actual wavelet changes spatially, in this abstract, the author adapts the original method to use space-varying wavelets to do spectral decomposition and shows the improved results.

Introduction

Since spectral decomposition was first introduced (Partyka, 1999) into seismic interpretation there have emerged several methods - varying from the popular short time Fourier transform (STFT) and continuous wavelet transform (CWT), to less frequently used other methods. Each method has its own advantage and disadvantages, but all methods can be simplified as some kind of operation between the seismic data and serial kernel functions with closed form expressions. For example, in CWT a mathematic wavelet is used; in S-Transform a Gaussian function is used. The advantages of these methods are their speed and easy calculation. The disadvantage of these approaches is that they may not always suit the seismic data collected in different regions. The author proposed a method that is similar to CWT - however instead of using a wavelet derived from a mathematic expression, an actual wavelet is extracted from the seismic data. The direct benefit, comparing to CWT, is that there are much less ringing or wavelet side-lobe effects while preserving the characteristics of CWT. The proposed method used an algorithm similar to CWT, wherein the seismic data is convolved with groups of dilated, squeezed and stretched seismic wavelets. If the closed form expression of a wavelet is known, squeezing and stretching can be easily done. Doing this with the discrete seismic wavelet is challenging. All these squeezing and stretching are based on a single extracted wavelet. After the method has been used in many real projects, it is found that using a single wavelet becomes less optimal. The author introduces an adapted method in this study; to use space-varying wavelets to do spectral decomposition and the same 3D seismic data set as used in the original method is used to compare the results.

Theory and Method

In seismic, spectral decomposition is done by convolving a seismic trace $s(t)$ with a kernel function, $h(t,\tau)$, as expressed as

$$S(\omega,\tau) = < s(t), h(t,\omega,\tau) >, \quad (1)$$

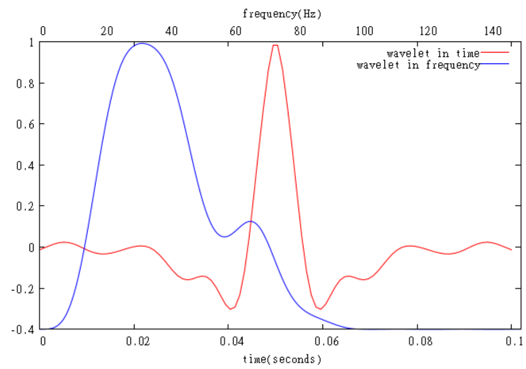
where t represents time, ω represents frequency and τ represents time shift. It actually is a localized spectra of the input signal. In case of CWT (Mallat, 2008), the kernel function,

$$h(t, \sigma, \tau) = \frac{1}{\sqrt{\sigma}} \psi(\frac{t-\tau}{\sigma}) \tag{2}$$

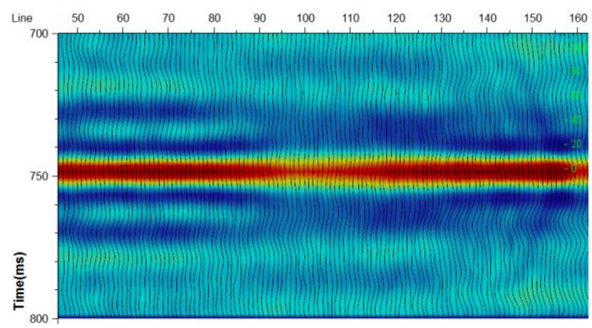
where ψ is the mathematic wavelet that can have different closed-form expressions, among which Morlet wavelet ($\frac{1}{\sqrt{2\pi}} e^{i\omega_0 t} e^{-t^2/2}$) is a commonly used one. In CWT, ψ is called the mother wavelet. It can be squeezed and stretched simply by changing the scale σ. This can be done in either the time (ψ) or the frequency (Ψ) domains because of the relationship.

$$\psi\left(\frac{t}{\sigma}\right) \leftrightarrow |\sigma|\Psi(\sigma\omega) \quad . \tag{3}$$

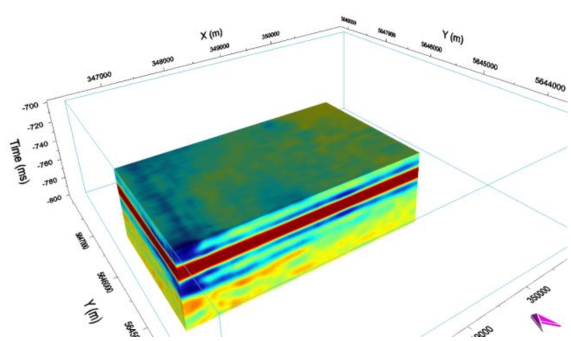
Spectral decomposition with CWT has some advantages comparing to STFT and some other methods and is a preferred option during interpretation. However, the ringing or side-lobe artifacts observed with this approach occur mainly because the wavelets used in CWT do not suit seismic data in many cases. The new method uses the real seismic wavelet instead of the closed-form mathematic wavelets. The real seismic wavelet is actually extracted from the seismic data and it varies with different seismic data and varies in different location even in the same data set. The extracted seismic wavelet is squeezed, stretched and then convolved with the seismic trace. The amount of squeeze and stretch can be estimated by equation (3). For example, a seismic wavelet with the dominant frequency of 30Hz, σ needs to be equal to 2 to compute spectral decomposition at 60Hz. If σ is not an integer number, the squeeze and stretch cannot be easily done. As an alternative approach I have chosen to use an interpolate-resampling technique. The wavelet is first densely interpolated and then resampled according to the amount of squeeze and stretch desired.



(a) The wavelet extracted from the entire dataset



(b) The extracted wavelets along a cross line



(c) The extracted wavelets shown in 3D

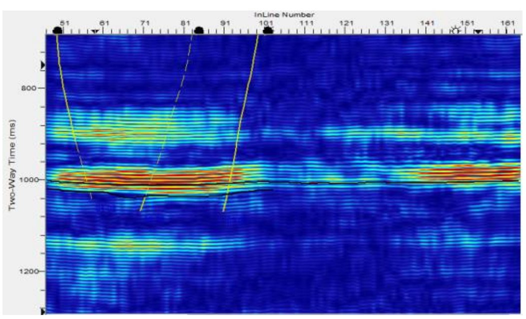
Figure 1: The extracted wavelet from Blackfoot P-wave seismic data.

In data sets where the actual seismic wavelet changes significantly, space-varying wavelets need to be used instead of a single extracted wavelet. These wavelets are generated by extracting one wavelet at each location within a predefined window. All the wavelets are then put together to form a wavelet volume.

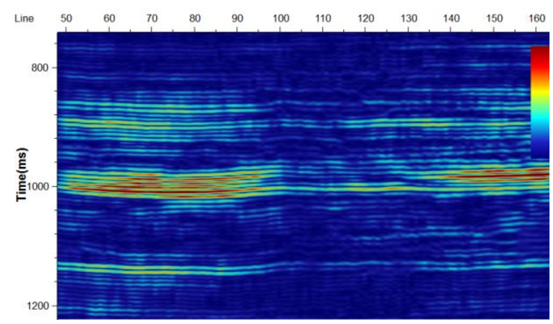
Figure 1(a) shows an extracted wavelet of Blackfoot (Blackfoot field near Strathmore, Alberta, Canada) P-wave seismic data in both the time (red) and frequency domains (blue). Figure 1(b) shows a section of extracted wavelets along cross line direction. Figure 1(c) is a 3D display of the extracted wavelet volume. The spatial change of the wavelets can be clearly seen. Once the wavelets have been extracted, and the extracted wavelets have been squeezed and stretched, based on the desired frequencies used in spectral decomposition they are subsequently convolved with the seismic trace to produce the spectra. It can be done either in the time or frequency domains.

Examples

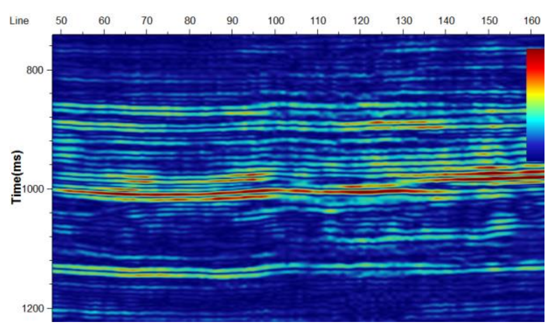
To illustrate the new method, the spectral decomposition results at 72Hz using three methods on a cross line in Blackfoot P-wave data are displayed in Figure 2. Figure (a), (b) and (c) display results using CWT, the new method with a single extracted wavelet and the new method with space-varying wavelets respectively. The wavelets used in Figure 2(c) is shown in Figure 1(b). Comparing the results it is clear that the new methods display a clear advantage over the CWT method in that less ringing effect is observed - especially in the three high energy event groups (corresponding to warm colours). Similar improvements can be observed at other frequencies. The method using space-varying wavelets generates better results with further less ringing effect than the method using a single extracted wavelet. For example, the weak events above and below the third strong event group (at around 1140ms, composed of two adjacent strong reflections) are much weaker, or even invisible in Figure 2(c) where space-varying wavelets are used.



(a) CWT result at 72Hz



(b) Result using single extracted wavelet at 72Hz



(c) Result using space-varying wavelets at 72Hz

Figure 2: Comparison of spectral decomposition methods on a cross line in Blackfoot data set.

Conclusions and discussions

A new spectral decomposition method using the space-varying extracted seismic wavelets, rather than the mathematic wavelets, is proposed. The extracted wavelets are numerically squeezed, stretched and then convolved with seismic data samples. The results of this study display less ringing or side-lobe effects compared to results from CWT. The method using space-varying wavelets is also superior to the method using a single extracted wavelet in that further less ringing effects are achieved. This space-varying extracted wavelet volume may also serve as a new kind of seismic attribute for direct interpretation, but this needs further investigation. Figure 3 shows a map view of this wavelet volume - it looks like it is in some way associated with the underline geology. Note that when extracting wavelets, in vertical direction, only a portion of data is used. So only the geology within that portion of data is reflected.

Since the squeeze and stretch of the wavelet in the new approach has to be done numerically, the computation cost would increase. However, if a single wavelet is used the additional calculations need only be done once for the entire data set. Therefore the increased computation cost can be minimized. Where space-varying seismic wavelets are used, the computation cost is increased, especially in part the entire wavelet volume has to be generated. Once the wavelets are extracted, the actual additional computation of spectral decomposition is still small.

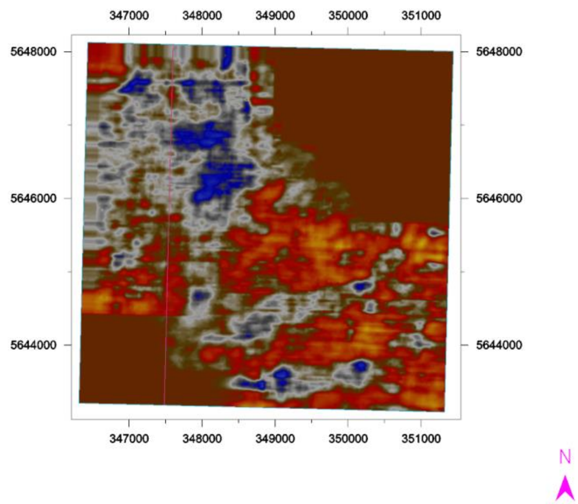


Figure 3: The map view of the extracted wavelet volume.

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