Time-Frequency Attribute of Seismic Data using Continuous Wavelet Transform

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Summary

A time-frequency decomposition that can provide higher frequency resolution at lower frequencies and higher time resolution at higher frequencies is desirable for analyzing seismic data. This is because the hydrocarbons in the reservoir are diagnostic at lower frequencies and thin beds can be resolved with enhanced time resolution at higher frequencies. In this paper we present a new method to compute the time-frequency spectrum using wavelet as a window that achieves this objective. Time-frequency spectrum is commonly used to compute various frequency attributes of seismic signal like single frequency, dominant frequency, center frequency and so forth. The conventional approach is to use short time Fourier transform (STFT) to obtain a time-frequency spectrum. Time-frequency resolution in the STFT is limited by the choice of a window length. The proposed time-frequency spectrum using CWT (TFCWT) in this work has the ability to adapt with the frequency content of the signal. The flexibility of not having to choose a window is an advantage of our method. We present two applications of TFCWT to real data sets in this paper. In the first example, we use TFCWT to enhance low frequency shadows caused by hydrocarbon reservoirs. In the second example, we apply the time frequency spectrum in interpreting time slices from a 3D seismic volume in frequency space to identify thin beds below tuning thickness.

Introduction

Time-Frequency localization of non-stationary signals, like seismic signals, is conventionally achieved by STFT. It produces a time-frequency spectrum whose time-frequency resolution is fixed by the choice of a time window. However, it is desirable to obtain a time-frequency spectrum that would adjust its resolution depending on the frequency content of the signal. This is achieved by convolving the signal with a wavelet that dilates to produce different frequency ranges. This methodology is called continuous wavelet transform (Daubechies, 1992; Goswami and Chan, 1999; Mallat, 1999).

Dilating support of a wavelet, scale as it is called, represents a frequency range and not a single frequency. Therefore, instead of a time-frequency map, a time-scale map is produced with CWT. The TFCWT method developed in this work converts scale into a single frequency. Since it utilizes self-adjusting wavelet as a window, it bypasses the requirement of a user specified window length, a drawback of STFT. In the next section we outline briefly the methodology to obtain TFCWT.

Theory

Time frequency spectrum using STFT is obtained by taking the inner product of a signal $f(t)$ convolved with a window function $g(t-\tau)$ in the Fourier domain. This is given by

$$F_{STFT}(\omega,\tau) = \int_{-\infty}^{\infty} f(t)\,\bar{g}(t-\tau)\,e^{-i\omega t}\,dt \, . \qquad \text{--- (1)}$$

Where, $\bar{g}$ is the complex conjugate of g, τ is the center of the chosen time window. CWT is defined as the inner product of a family of wavelets $\psi_{\sigma,\tau}(t)$ with the signal $f(t)$. This is given by

$$F_W(\sigma,\tau) = \int_{-\infty}^{\infty} f(t)\,\frac{1}{\sqrt{\sigma}}\,\bar{\psi}\left(\frac{t-\tau}{\sigma}\right)dt \, . \qquad \text{--- (2)}$$

Where, σ is the scale, $\bar{\psi}$ is the complex conjugate of ψ, τ is the translation parameter and $F_W(\sigma,\tau)$ is the time-scale map (Scalogram). By taking the Fourier transform of the inverse continuous wavelet transform we can convert the time-scale map into the time-frequency map. This is given by

$$F_{TFCWT}(\omega,\tau) = \frac{1}{C_\psi}\int_{-\infty}^{\infty} F_W(\sigma,\tau)\,e^{-i\omega\tau}\,\psi(\sigma\omega)\,\frac{d\sigma}{\sigma^{3/2}} \, . \qquad \text{-- (3)}$$

Where, ^ represents a function in the Fourier domain and C_ψ is a wavelet dependent constant. Time-frequency map, thus produced in eq (3) is called TFCWT. Equation (3) is the fundamental result used in this work to compute time frequency spectra of seismic data. The details of the method and the algorithm can be found in Sinha, 2002.

Synthetic Example

In this section we illustrate the method using a synthetic chirp sweep. A synthetic chirp signal having two hyperbolic sweep frequencies increasing with time is analyzed by the above two methods (i.e. STFT and TFCWT). The chirp signal is sampled at 4 ms. Time-frequency map with STFT is produced using 400 ms hamming window shown in Figure 1. It indicates that the low frequency components are well resolved compared to the higher frequencies since the chosen time window is too broad. Choosing a shorter window length will compromise the frequency resolution to obtain higher time resolution. Therefore, analyzing a non-stationary signal with STFT has a practical limitation of choosing an appropriate window length. However, time-frequency map from TFCWT shown in Figure 2 does not require any window length. We also observe that the time-frequency resolution is significantly better as compared to that in the Figure 1.

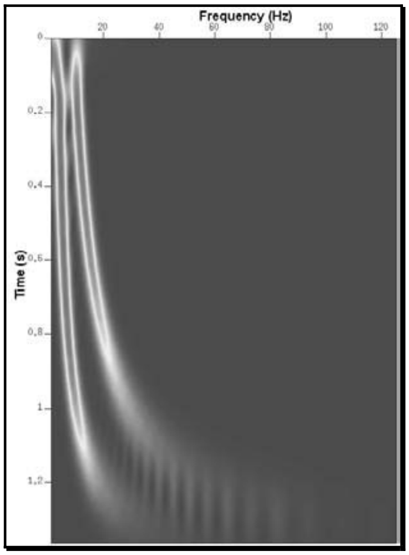

Figure 1: Time-Frequency spectrum of chirp signal with two hyperbolic sweep frequencies produced from STFT using 400 ms Hamming window.

Applications of TFCWT to Seismic Data

Interpretation and visualization of seismic data in the frequency domain is an important tool to study the geological information in a region. Typically such analysis is carried out with post-stack data sets. In this procedure a seismic signal is mapped into time-frequency plane using either STFT or TFCWT or other time-frequency analysis method. In the time-frequency space, interpretation can be made by taking a single frequency amplitude or power as the seismic attribute. Two different ways of interpreting seismic data in frequency space are illustrated.

A. Single Frequency Seismic (SFS) section

Time-frequency analysis of a one dimensional trace produces two dimensional data set by adding a frequency axis and a two dimensional seismic section generates a 3D data volume with the third axis being frequency up to the Nyquist. Any section at a single frequency from this 3D data volume is called a *single frequency seismic (SFS)* section. Comparison of different SFS sections can be utilized to detect low frequency shadows caused by hydrocarbon reservoirs. This method can potentially be utilized for direct hydrocarbon detection (Sun, Castagna and Siegfried, 2002).

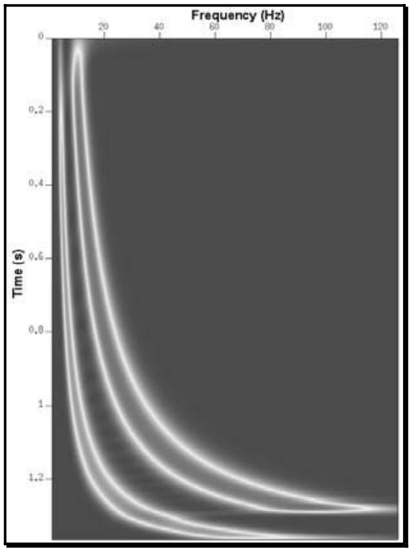

Figure 2: Time-Frequency map of a chirp signal analyzed with TFCWT using Morlet wavelet.

A seismic section from Ukpokiti, Nigeria shown in Figure 3 is interpreted using this method. Bright amplitudes in the data are indicative of hydrocarbon zones. An SFS section at 20 Hz from the TFCWT data volume shows high amplitude low frequency anomalies (colored as red) at the reservoir level in Figure 4. At 33 Hz these anomalies disappear as shown in Figure 5. The anomaly above the hydrocarbon reservoir level in 33 Hz section is due to local tuning effect which does not disappear at higher frequencies. This example shows that the comparison of SFS sections from TFCWT have been able to detect low frequency shadows caused by hydrocarbon.

B. Single Time-Frequency (STF) Slice

Addition of frequency axis to 3D seismic data volume makes the time-frequency volume 4D and makes the visualization difficult. To make visualization simple, a 3D seismic data volume can be rearranged in 2D according to trace number or CDP. Time-frequency analysis on this data will extend it in the third dimension adding a frequency axis to it. From this time-frequency-CDP volume, we can take a slice at fixed time and rearrange the trace numbers according to their inline and crossline numbers to produce a frequency-space cube. Visualization of frequency slices (i.e. single time-frequency slices) from such a 3D cube can be utilized for thin beds identification and reservoir characterization.

A time-slice has been taken from the Waha-Lockridge 3D seismic data volume shown in Figure 6. A channel feature is indicated in blue. An important geological question is: whether the channel ends in the middle of the area or is it beyond the resolution capability of the seismic because of thin bed? From an interpreter's point of view the extension of this channel feature is crucial information for reservoir characterization. A 20 Hz frequency slice for the same time slice presented in Figure 7 is not indicative of the channel. A possible interpretation would be that the channel is not thick enough to tune at 20 Hz. For the same time-slice the 40 Hz section in Figure 8 shows the channel feature similar to the amplitude section in Figure 6. It is important to note that the dominant frequency of the seismic data is about 40 Hz. Therefore, the 40 Hz slice shows similar feature as the amplitude section. At 95 Hz time slice shown in Figure 9, the channel feature is greatly enhanced and we can see a thin meandering channel at the bottom center. Such analysis is important for reservoir characterization so that petroleum engineers can constrain fluid flow for reservoir simulation studies. Results from both the field applications with TFCWT on the 2D (Ukpokiti) and 3D (Waha-Lockridge) data sets are very encouraging.

Conclusions

In this paper we have developed a new method (TFCWT) to compute time frequency spectrum using wavelets as the window. Conventional method like STFT has inherent drawback of selecting a window length that makes the processing and interpretation subjective. TFCWT overcomes this problem and gives a more robust technique for time-frequency attribute analysis. The dilation and compression of wavelets effectively provides the optimal window length depending upon the frequency content of the signal, thus eliminating the subjective choice of a window length. The computation of the CWT in the Fourier domain provides the flexibility to compute the time frequency map without much effort. Synthetic example presented in the paper shows the advantage of our method over the STFT. The field examples on frequency attribute computed using TFCWT presented in this work provide optimism that single frequency sections can potentially be utilized as a direct hydrocarbon indicator and single time-frequency slices can be used to enhance thin bed reservoirs.

References

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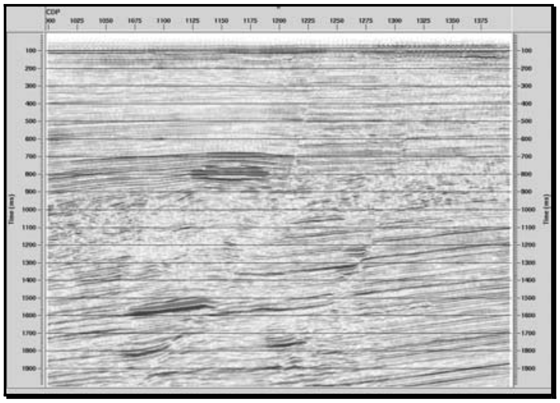

Figure 3: A seismic section from Ukpokiti, Nigeria showing hydrocarbon zones as bright amplitudes adjacent to faults.

Time-Frequency Attribute

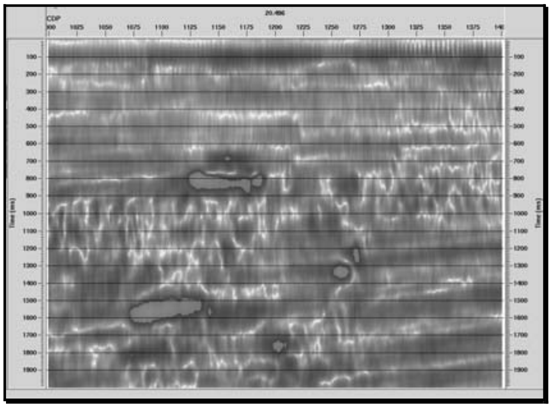

Figure 4: A 20 Hz single frequency seismic section showing anomalies at the hydrocarbon reservoir levels.

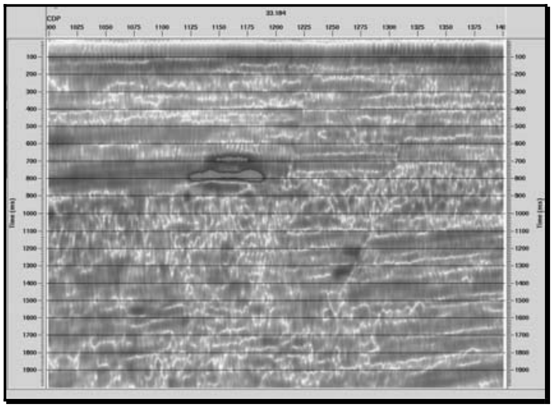

Figure 5: Low frequency high amplitude anomaly in Figure 4 disappeared in this 33 Hz SFS section. Anomaly in this figure is due to tuning of thin beds.

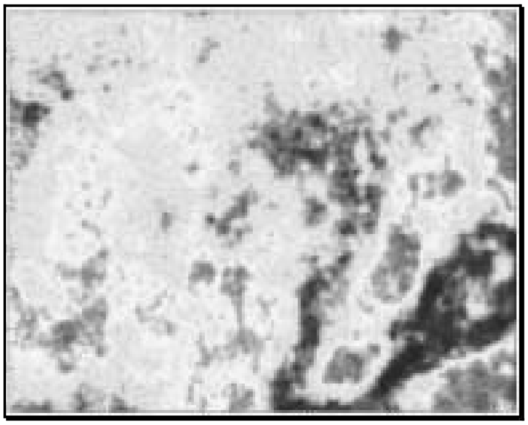

Figure 6: A time slice from Waha-Lockridge 3D data volume showing a channel feature in blue.

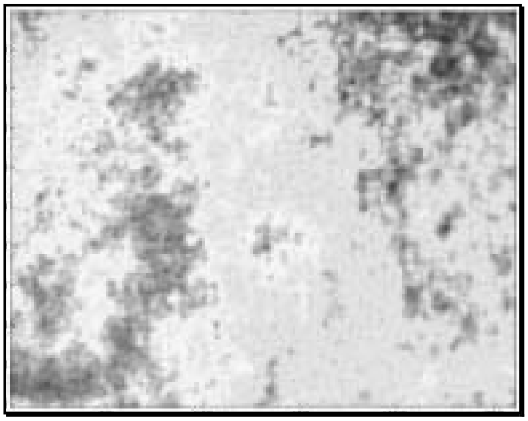

Figure 7: This is a 20 Hz STF slice. The channel feature is not thick enough to tune at 20 Hz.

Figure 8: The channel feature reappears in 40 Hz STF slice. Dominant frequency of the data is also about 40 Hz.

Figure 9: At 95 Hz extension of the channel is seen in the bottom left part.