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Recent Developments in Spectral Decomposition of Seismic Data (Techniques and Applications): A Review

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Summary

This paper presents a review of spectral decomposition of seismic data, since it's inception nearly in 1997. It discusses various techniques and applications of spectral decomposition in seismic data processing and interpretation. It is also known as time-frequency analysis consists of transforming non stationary signal in time/space from time/space domain to time/space vs frequency domain. The frequency domain representation illustrates many important features that are not apparent in time domain representation. Spectral decomposition is a non-unique process for which various techniques exists and newer modified techniques are being discovered. Over the years, spectral decomposition of seismic data has progressed from tool for stratigraphy analysis to direct hydrocarbon indicator (DHI) technique. This technique is mostly used by seismic interpreters and being DHI, it is a potential weapon for minimizing dry well drilling. In coming time, spectral decomposition may can play a significant role in analyzing time lapse seismic data.

***Keywords**: Spectral decomposition, Time-frequency analysis, Direct hydrocarbon indicator, Matching pursuit decomposition.*

Introduction

Spectral decomposition of seismic data is a mathematical tool of transforming seismic data from time domain to time vs frequency domain. It converts one dimensional seismic trace in time domain to two dimensional time vs frequency domain representation, thus provides information on variation of frequency with time. In a similar way, it converts two dimensional seismic section to three dimensional representation, third axis being frequency. The frequency domain representation of seismic data illustrates many features that are not apparent in time domain representation and hence spectral decomposition serves as an useful tool for seismic interpreters.

Early work

Early research work on spectral decomposition was performed by Greg Partyka. He introduced concept of spectral decomposition and was eventually awarded by SEG Virgil Kauffman Gold Medal in 2003 for the same (Cooper, 2004; Partyka, 2007). Gridley and Partyka (1997) used STFT based spectral decomposition to analyse seismic features as a function of frequency amplitude and phase which is helpful in interpretation. Partyka et al. (1999) used spectral decomposition for imaging and mapping temporal bed thickness and geologic discontinuities in 3D seismic data.

Present status

Currently, research in spectral decomposition can be broadly classified into two categories. In the first category (Category-A), researchers are trying to discover newer and accurate techniques for time-frequency analysis of seismic trace. In the second category (Category-B), researchers are trying to identify novel applications of spectral decomposition in studying different geological environment.

Category-A: Research in developing advanced techniques of spectral decomposition

Basic time-frequency analysis technique is Fourier transform which is an excellent tool to study stationary signals. For stationary as well as non-stationary signals, Fourier transform provides global picture of frequency in signal but incapable of providing local variation of frequency. The immediate solution that was put forward by Dennis Gabor for time-frequency analysis of non-

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stationary signals was STFT (Gabor, 1946). STFT provides local variation of frequency but suffers from the time-frequency resolution limitation (due to fixed window size) (Chakraborty and Okaya, 1995; Sun et. al., 2002). Advanced techniques of Spectral decomposition of seismic data were developed in course of time such as S transform (Odebeatu et al., 2006), Continuous-wavelet transform (CWT) (Sinha et al., 2005), Wigner-Ville distribution (WVD) (Li and Zheng, 2008) and Matching pursuit decomposition (MPD) (Mallat and Zhang, 1993). Over the years, researchers have developed their own methods which are modified forms of one or more basic techniques as follows.

STFT based techniques: Qiang and Wen (2010) have used deconvolutive short time Fourier transform for spectral decomposition of seismic signals. Puryear et al. (2012) developed an algorithm called "constrained least-squares spectral analysis" for time-frequency analysis of seismic trace. This algorithm contains modified form of STFT and claimed to provide superior temporal resolution than STFT and CWT. Wenkai and Fangyu (2013) have modified the deconvolutive short-time Fourier transform method proposed by (Lu and Zhang, 2009) by applying a 2D deconvolution operation on STFT spectrogram and tested on seismic data from North Tarim Basin, Western China.

S transform based techniques: Odebeatu et al. (2006) applied S transform to seismic data and observed spectral anomaly attributed to gas bearing rocks. Reine et al. (2009) have compared the performance of various methods of spectral decomposition for measuring seismic attenuation. They concluded that S transform and wavelet transform outperforms other methods such as STFT and Gabor transform.

CWT based techniques: Sinha et al. (2003) have developed a novel method of calculating time-frequency spectrum using CWT which they report as TFCWT. Spectral decomposition with TFCWT are used to detect low frequency shadows caused by hydrocarbons and to identify subtle stratigraphic features for reservoir characterization (Sinha et al., 2005). TFCWT algorithm are also used for calculating instantaneous spectral attributes (Sinha et al., 2009). Castagna et al. (2003) have commented on FFT, STFT, maximum entropy method (MEM), CWT and have used wavelet-transform based instantaneous spectral analysis (ISA) which provides better time and frequency resolution. Zhang (2008) developed continuous wavelet packet-like transform (CWPT) which is an extension of the CWT.

WVD based techniques: Li and Zheng (2008) have used smoothed Wigner-Ville distribution (SWVD) based spectral decomposition on seismic data from the Central Tarim Basin. Zhang (2008) introduced chirplet transform and combined it with WVD to do spectral decomposition.

MPD based techniques: Chakraborty and Okaya (1995) have performed time-frequency analysis of seismic traces using STFT, CWT and MPD developed by Mallat and Zhang (1993), and discussed the results. They further carried out MPD based time-frequency analysis on prestack seismic traces from Siljan and Sweden, and found frequency anomalies associated with first arrival traveltime, surface waves and other events on traces. Sun et. al. (2002) have discussed enhanced spectral processing (ESP) technique which is based on spectral analysis using MPD and gives better resolution than other methods. Castagna and Sun (2006) have developed exponential pursuit decomposition (EPD), which is modified form of MPD and is laterally more stable than MPD. Wang (2007) improved MPD by using complex-trace attributes for a preliminary estimation of parameters for constituent wavelets and used it for detecting low-frequency shadow associated with a carbonate gas reservoir.

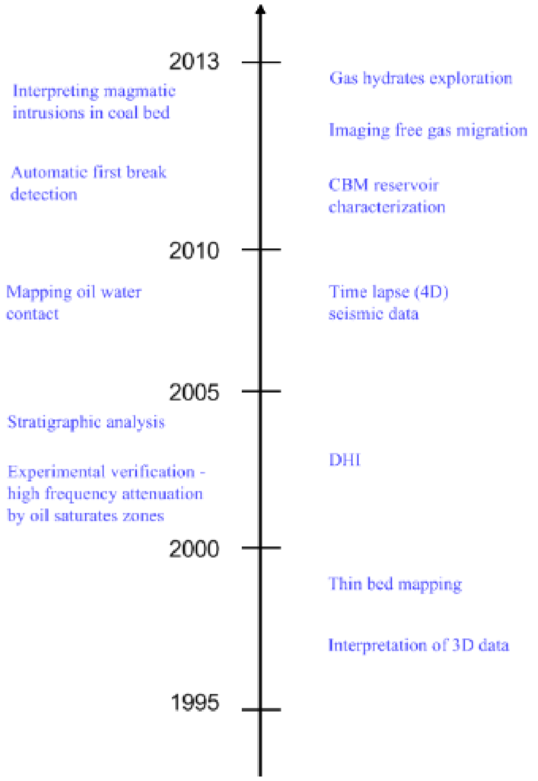

Figure 1: A time line of different applications of spectral decomposition.

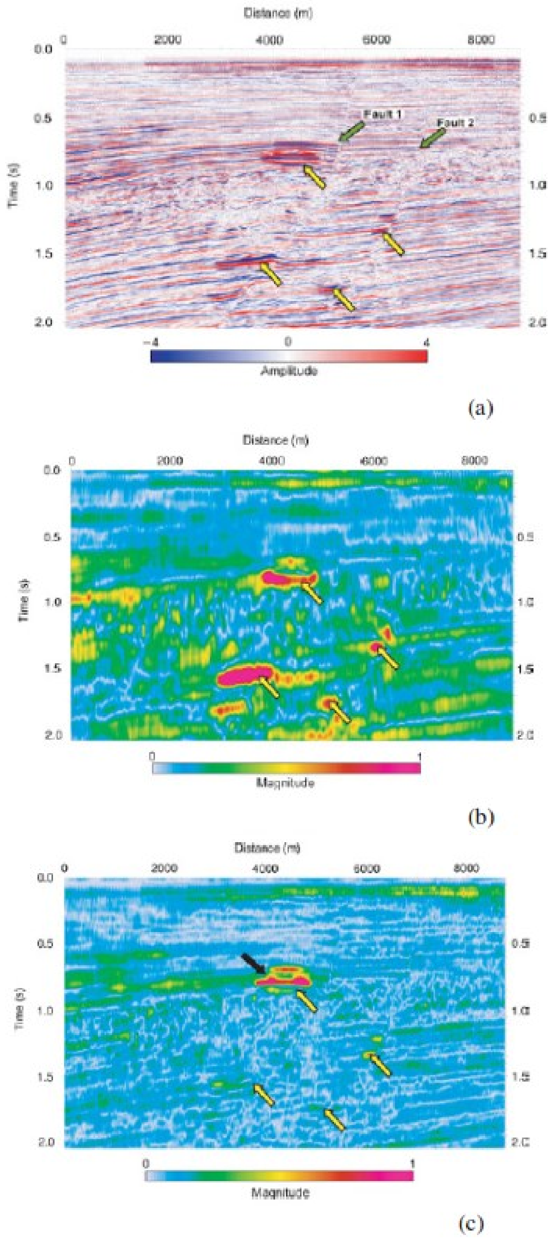

Figure 2: a) A seismic section from a Nigeria data set. Yellow arrows indicate known hydrocarbon zones while green arrows indicate faults. b) A 20 Hz frequency slice obtained after spectral decomposition. High-amplitude low frequency anomalies (red) at hydrocarbon zones are apparent. c) A 33 Hz frequency slice where amplitude of frequencies at known hydrocarbon zones (yellow arrows) is very low (after Sinha et al., 2005).

Other techniques: Hao et al. (2011) developed frequency slice wavelet transform (FSWT) which is a new method of time-frequency analysis and tested it on synthetic and real field seismic data. Liu et al. (2011) developed new algorithm using an iterative inversion framework for time frequency analysis. They demonstrated the method for detecting channels and low-frequency anomalies in seismic images. Recently complete ensemble empirical mode decomposition (CEEMD) has been developed and tested by Han and Baan (2013). That method produces smoothly varying and positive instantaneous frequencies suitable for time-frequency analysis and outperforms STFT and CWT in terms of time-frequency resolution.

Why different techniques ?: After reviewing different techniques, a questions arises what is the need for so many techniques? Castagna and Sun (2006) have answered the question with detailed discussion. They mentioned that spectral decomposition technique can be categorized as 'useful' or 'not useful' for the specific application and not as 'right' or 'wrong'. All these techniques have characteristic merit and demerit and different techniques are required for different applications (Castagna and Sun, 2006).

Category-B: Different applications of spectral decomposition

Since inception, spectral decomposition have been used for various purposes. A time line of different applications of spectral decomposition is shown in Figure 1.

Spectral decomposition as DHI: It was known for many years that hydrocarbon bearing sedimentary rocks show frequency dependent seismic attenuation. Tanner et al. (1979) observed low frequency shadows on reflections from reflectors below gas sands and oil reservoirs. Spectral decomposition is a potential tool for characterizing this peculiar behaviour of rocks which is difficult otherwise. When spectral decomposition is carried out on seismic data collected in hydrocarbon proven region, resultant frequency slices show frequency anomalies i.e. low frequency slices show higher amplitude than corresponding high frequency slices at hydrocarbon zones. Thus, this technique acts as DHI and can play a major role in minimizing dry well drilling. Sun et. al. (2002) have discussed low frequency shadows associated with hydrocarbons. Castagna et al. (2003) have identified high amplitude low frequency anomalies in seismic data from the Gulf of Mexico and from the NW Shelf of Australia. Team of Goloshubin performed ultrasonic laboratory experiments in which a physical model was created which consisted of sandstone layer with dry, water and oil saturated zones. Study of recorded reflected waves validated that oil saturated zone of sandstone causes loss of high-frequency energy (Goloshubin et al., 2002). Sinha et al. (2005) carried out spectral decomposition of seismic section from a Nigeria data set as shown in figure 2, and observed high amplitude low frequency anomalies associated with known hydrocarbon zones. Xiaodong et al. (2011) have used this DHI for hydrocarbon detection in the Manan on Basin in Peru.

Other applications (2001-2010): Marfurt and Kirlin (2001) derived a suite of attributes from spectral decomposition volumes to efficiently map stratigraphic features, particularly fluvial channels. Burnett et al. (2003) carried out spectral decomposition of seismic data from the Burgos and Macuspana basins of Mexico and obtained preferential reservoir illumination and clear picture of reservoir. Goloshubin et al. (2006) used frequency slices obtained after spectral decomposition for mapping oil-water contact which aids in reservoir management. Liu and Marfurt (2007) showed that spectral decomposition can be used to map subtle changes in thickness of channels filled with porous rock and encased in a nonporous matrix. Li and Zheng (2008) have applied spectral decomposition on seismic data from the Central Tarim Basin, China and found high amplitude high-frequency anomalies associated with reef and shoal facies belt of carbonate reservoir. Oliveira et al. (2010) used spectral decomposition to delineate gas hydrates concentration and to interpret free gas accumulations in Pelotas basin.

Other applications (2011-13): Automatic first break detection of p-waves and s-waves by spectral decomposition requires minimum uncertainty wavelets (Liao et al., 2011). Duchesnea et al. (2011) used spectral decomposition for detecting hydrocarbon migration from deep reservoirs to the seafloor. They attempted this interpretation method on seismic data from offshore Queen Charlotte Basin which hosts several seafloor pockmarks and mounds. Wang (2012) used spectral decomposition in conjunction with clustering analysis technique for coal bed methane (CBM) reservoir characterization. Ruiz and Aldana (2012) used multi-attribute analysis and spectral decomposition to study heavy oil reservoirs at the south flank of the Maturín Sub-Basin. Nyamapfumba and McMechan (2012) used spectral decomposition for interpreting free gas distribution in 3D seismic data collected in gas hydrates proven offshore Angola. Yoon and Farfour (2012) used spectral decomposition to image stratigraphic features and confirmed the results obtained from AVO analysis and inversion of seismic data from Blackfoot field, Alberta, Canada. Recently magmatic intrusions into a coal bed were detected by using spectral decomposition (Wang et. al., 2012). Liu and Fomel (2013) used spectral decomposition for seismic ground-roll noise attenuation and multicomponent data registration.

Future advancements

In the coming few years, the quest for discovering more accurate spectral decomposition technique will continue resulting optimal technique. With the more accurate technique, it will be possible to delineate oil and gas distribution in hydrocarbon bearing region optimally. Over the past few years, time lapse seismic methods (also called as 4D seismic) have been increasingly used for reservoir monitoring (Johnston et al., 1998; Lumley, 2001). The primary objective of time lapse seismic methods is to image fluid flow in the inter well region. Currently few studies have been reported on application of spectral decomposition to 4D data (Rojas and Davis, 2009; Zhao et al., 2006). In future, spectral decomposition will play a vital role for interpreting fluid flow from 4D seismic data and hence will be useful for managing enhanced oil recovery techniques and for reservoir surveillance. The use of spectral decomposition for exploration of gas hydrate and CBM is at nascent stage at present and will rise in future.

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