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Application of the empirical mode decomposition and wavelet transform to seismic reflection frequency attenuation analysis

Ya-juan Xue [a,b,c,*], Jun-xing Cao [a,c,*], Ren-fei Tian [c,d], Hao-kun Du [a,c], Ya-xiang Shu [a,c]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China
[b] School of Communication Engineering, Chengdu University of Information Technology, Chengdu 610225, China
[c] School of Geophysics, Chengdu University of Technology, Chengdu 610059, China
[d] Postdoctoral Workstation of Sinopec Henan Oilfield Company, Zhengzhou 450046, China

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ABSTRACT

Frequency attenuation analysis is a useful tool for direct hydrocarbon indication. Frequency attenuation gradient is more sensitive to the type of reservoir identification than other frequency properties such as center frequency, root-mean-square frequency. One of the derived properties for direct hydrocarbon detection is time–frequency spectral decomposition. Based on seismic attenuation theory in a fluid-filled porous medium, a new method combining the Empirical Mode Decomposition (EMD) and the continuous-wavelet transform named EMDWave is proposed as a high-precision frequency attenuation analysis and an improved time–frequency analysis methods. Compared to the Hilbert–Huang Transform (HHT) method, it reflects more details. The common frequency section calculated by the EMDWave method can improve the reservoir characteristics. First, the EMD method is used as multiband filtering in the temporal domain. The EMD method can decompose the original seismic signals into a finite number of Intrinsic Mode Functions (IMFs). All these IMFs can be expressed as gradual single-frequency signals that enhance the physical meaning of instantaneous frequencies and instantaneous amplitudes. After the correlation analysis of the original seismic signal and its corresponding IMFs, the IMF component which reflects more oil and gas information is selected for further hydrocarbon detection. The selected IMF with relatively narrow band can make the wavelet transform avoid the frequency loss incurred by a large scale distribution for broadband non-stationary signals. Second, the wavelet transform is applied to the selected IMF. The time–frequency spectrum obtained has a single-peaked spectrum with narrow side-lobes and it is good for computing the absorption coefficients. Then absorption coefficients are computed by curve fitting based on the least square method. The proposed method EMDWave effectively improves the precision of the conventional methods of Energy Absorption Analysis (EAA). Applications of the EMDWave method for hydrocarbon detection over a gas field located in western Sichuan Depression, China, show the effectiveness of gas bearing detection. It can improve the traditional attenuation analysis for better reservoir characterization.

1. Introduction

Both laboratory and field data measurements show that the attenuation of seismic waves is more pronounced for viscous fluid–saturated rocks than for dry rocks over most of the frequency bandwidth (Dvorkin and Nur, 1993; del Valle-García and Ramírez-Cruz, 2002; Korneev et al., 2004). Scattering and absorption are the main factors that contribute to the attenuation of seismic waves (Duchesne et al., 2011). Anderson and Hampton (1980) propose that scattering is the main attenuation mechanism for higher frequencies as they are attenuated more rapidly than lower frequencies in gas-prone sediments. Amplitude anomalies that result from attenuating media can be used as hydrocarbon indicators. Some efforts have been made to use the physics of seismic attenuation for reservoir detection. Winkler and Nur (1982) studied seismic wave attenuation in rocks experimentally and found that the ratio of compressional to shear attenuation is a more sensitive and reliable indicator of partial gas saturation than the corresponding velocity ratio. Clark et al. (2001) found that the magnitude of attenuation change with azimuth can be served as a useful indicator of fracture direction in fractured media. del Valle-García and Ramírez-Cruz (2002) showed that changes in the spectral and amplitude characteristics of the seismic signals are associated with the presence of fluids and fractures within a fractured carbonate reservoir. Maultzsch et al. (2007) observed

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* Corresponding authors.
E-mail addresses: xueyj0869@163.com, xueyj0869@cuit.edu.cn (Y.-j. Xue), caojx@cdut.edu.cn (J.-x. Cao), tianfei906@sohu.com (R.-f. Tian), dhk20052005@163.com (H.-k. Du), stormeyecloud@gmail.com (Y.-x. Shu).

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azimuthal variations in P-wave attenuation by the analysis of a multi-azimuth walkaway VSP data set from a fractured hydrocarbon reservoir and further modeled the observed effects. Their study suggests the validity of the link between the anisotropic attenuation and the fracturing. Duchesne et al. (2011) used time–amplitude and time–frequency information from seismic reflection data sets of different resolutions to analyze anomalous reflections from very-shallow to great subsurface depths and determined the nature of fluids in the subsurface and further confirmed that the amplitude anomalies were associated with low-frequency shadows attributed to the occurrence of gas.

Mitchell et al. (1996) proposed the Energy Absorption Analysis (EAA) method that computes the absorption coefficient for the estimation of the high frequencies that are absorbed by the media. Recently, the EAA has been widely used in hydrocarbon detection (see, for example, Martin et al., 1998; Xiong et al., 2011). The traditional EAA uses the method of two-point slope and can only be used on high S/N seismic signals.

Seismic wave attenuation can be measured with time-domain methods or frequency-domain methods or joint time–frequency methods. Among these methods, joint time–frequency methods have proven to be more robust in estimating instantaneous frequency and seismic attenuation (Tobback et al., 1996). Reine et al. (2009) found that variable-window time–frequency transforms such as continuous-wavelet transform (CWT) shows better robustness and accuracy for attenuation measurements than fixed-window transforms. Spectral decomposition from CWT has better time–frequency resolution than short-time Fourier transform (STFT), so the instantaneous spectral attributes from Wavelet transform are expected to be better than those from STFT (Sinha et al., 2009).

As a time–frequency analysis method, wavelet transform can be applied to obtain the instantaneous physical variables of a non-stationary signal (see, for example, Delprat et al., 1992; Gao et al., 1999; Scheper and Teolis, 2003). When the analytic wavelet is used to decompose the real signal in a certain scale, the decomposition results is an analytical signal that uses the Hilbert transform to determine instantaneous frequency of a signal (Van der Pol, 1946; Lilly and Olhede, 2010). From this wavelet transform the instantaneous frequency of every scale of the real signal is obtained. Wavelet transform provides a natural window for signals that requires high time resolution at high frequencies and high frequency resolution at low frequencies based on the dilation property of a wavelet and does not require preselecting a time window, which is essential in STFT (Sinha et al., 2009). The instantaneous attributes obtained by wavelet analysis have certain effects on the analysis of non-stationary signals such as edge detection (see, for example, Aydin et al., 1996; Schmeelk, 2005) and image compression (see, for example, Lewis and Knowles, 1992; Boix and Cantó, 2010), the time–frequency distribution in time series (see, for example, Farge, 1992), fault diagnosis (see, for example, Jena and Panigrahi, 2012) and lithological characteristics identification (see, for example, Perez-Muñoz et al., 2013) and gas detection(see, for example, Kazemeini et al., 2009).

Time–frequency spectrum obtained from CWT essentially involves converting a time-scale map obtained from the CWT into a time–frequency map. But for broadband non-stationary signals, some of the frequency component will be lost due to a larger range of scales distribution and the influence of discrete intervals of analysis imposed by the n number of scales. This will result in a decrease of the accuracy of the frequency calculations.

The Empirical Mode Decomposition (EMD) decomposes the original signal into a finite number of gradual single-frequency functions also known as Intrinsic Mode Functions (IMFs) (Huang et al., 1998). This method uses the local time scale characteristics of the data to decompose the signal without the need of predefined base function. Base function is adaptively generated with the signal in the EMD process. Therefore, each IMF component decomposed by the EMD contains the information on the local characteristics of the original signal and has certain physical meaning.

By observing the EMD behavior, Huang et al. state that EMD is just as we might do for some unknown “filter” in signal processing (Huang and Shen, 2005). It is proved that the EMD method acts essentially as a dyadic filter bank resembling those involved in wavelet decomposition (Flandrin et al., 2004). By using numerical examples of Gaussian band-pass noise Wang et al. also find that EMD acts as an adaptive, multi-band overlapping filter bank (Wang et al., 2012).

In this paper, having employed EMD to produce IMF, we test instantaneous spectral analysis and EAA based on the CWT for the first time and make the EMD combined EAA and wavelet transform named EMDWave well suit for non-stationary seismic signals analysis. We apply the EMDWave method to frequency attenuation analysis of the seismic data acquired over a marine carbonate reservoir in China. And the EMDWave method is expected to enhance the reservoir characteristics and given a more precise absorption coefficients estimation.

2. Theory and methods

2.1. Empirical mode decomposition (EMD)

The purpose of using EMD is to obtain IMFs (Huang et al., 1998). The internal vibration modes of the signal are characterized by the IMFs. That can be defined and distinguished through a sifting process. Each IMF involves only one mode of oscillation, since no complex riding waves are allowed (Huang et al., 1998).

After EMD decomposition, the original signal $X(t)$ can be expressed as

$$X(t)=C_1(t)+C_2(t)+\cdots+C_n(t)+R_n(t)=\sum_{i=1}^{n}\mathrm{Re}[a_i(t)\exp(j\theta_i(t))]+R_n(t), \tag{1}$$

where, $C_i(t)$ is the i-th *IMF* ($i=1\text{–}n$) and $R_n(t)$ is the residue. $a_i(t)$ and $\theta_i(t)$ are the instantaneous amplitude and the instantaneous phase of the i-th *IMF* $C_i(t)$ respectively. The details of EMD sifting process can be found in Huang et al. (1998).

End effects are one important limitation in implementing the EMD (Huang and Shen, 2005; Huang and Wu, 2008; Rato et al., 2008). There are many methods to adopt for end effects suppressing. Here, we chose the simple method of Huang et al. (1998) to avoid the end effects in our applications because there are always a large amount of seismic data to process in hydrocarbon detection.

For hydrocarbon detection, we only use the proposed method since it responds well to oil and gas occurrences. The whole picture or information of the original seismic data sometimes is not required. Each IMF has different frequency components, potentially highlighting different geologic and stratigraphic information. We only need to select the most appropriate IMF which contains the more main detailed information attributed to hydrocarbon content of the geological media in subsequent processing for hydrocarbon detection.

2.2. Instantaneous spectral analysis based on CWT

Spectral decomposition technique carries out the continuous time–frequency analysis for every seismic trace for the purpose of converting the original individual seismic volumes in the time domain to multiple frequency volumes (e.g. Partyka et al., 1999).

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