Fluid indicators based on velocity dispersion and attenuation from acoustic waveform in the carbonate reservoirs

Introduction

When travelling through the porous formation saturated fluid, acoustic wave makes vugs or fractures close and open, and causes the fluid to move relatively. Macroscopically, it shows the change of acoustic velocity, the loss of energy and the attenuation of amplitude. Therefore, the researches on acoustic velocity dispersion and attenuation based on the full-waveform multipole acoustic logging data are available to identify the fluid stored in fractures and vugs.

Frazer et al. (1997) developed the median frequency shift method to calculate the attenuation value of acoustic logging data. Baron and Holliger (2010) pointed out the characteristic frequency \( f_c \) to calculate permeability and the velocity difference of P wave to compute saturation. Tang et al. (2012) added the fracture density and aspect ratio parameters into the Biot’s poroelastic wave theory, then accurately predicted hydrocarbons from tight sand and shale gas formations. Suziki (2013) proved that the energy dissipation from the full-waveform sonic logging data is mainly intrinsic attenuation, and utilized waveform data from different receivers to correct the \( Q \) value computed by the median frequency shift method. Rubino et al. (2013) simulated the effect of fracture connectivity on acoustic attenuation mechanism. On the basis of Tang (2012), Chen et al. (2014) established the multipole acoustic propagation model suitable for fractured formations, and used P and stoneley wave to predict hydrocarbons. Xu et al. (2014) conducted numerical simulation of fractured-vuggy medium, and systematically analyzed the influences of different fracture density and gas saturation on P, S and stoneley waves received by multipole array acoustic tool. Bouchaala et al. (2016) applied the spectral ratio, median frequency shift and interferometry methods to estimate intrinsic and extrinsic attenuation from monopole and dipole sonic waveforms in the carbonate reservoirs. Sun et al. (2016) presented a filtering-semblance-correlation (FiSCo) method based on beamforming to analyze velocity dispersion of gas hydrate.

It is well known that carbonate rocks have high heterogeneity and complex lithology, so the estimation of acoustic velocity dispersion and attenuation is extremely complicated. There exists be few research achievements on the acoustic dispersion and attenuation in carbonate reservoirs. A frequency-division cross-correlation method based on slowness-time coherence (STC) which is utilized to estimate the velocity dispersion of P wave and characteristic frequency from the full-waveform multipole array acoustic logging data, discover the attenuation mechanism and rock physical properties in carbonate reservoirs. Moreover velocity dispersion increment \( \Delta v_{pf} \) and inverse quality factor \( Q \) can be served as good indicators of quantitative fluid evaluation in this research.

Frequency-division cross-correlation method based on STC

The frequency-division cross-correlation method based on STC is described to generate the velocity dispersion using the full-waveform multipole acoustic logging data in this section. The key of the novel method to determine the velocity dispersion is to find the arrival time of acoustic waves belonging to various frequencies. The array acoustic waves with similar waveforms appear regular in different traces. The travel time is used to analyze the similarity of any two waveforms (Kimball and Marzetta, 1984).

In term of the full-waveform multipole acoustic logging data, coordinates of the maximum value of the similarity matrix respectively correspond to the arrival time \( t \) and velocity of the P, S and stoneley wave \( v \). Therefore, it is particularly important to determine appropriate range of \( t \) and \( v \). To research velocity dispersion, the serial band-pass filters which are determined the optimal parameters by multi-taper tests, including shape, passband width and moving step length, are performed on the acoustic data. STC algorithm is applied to calculate each similarity matrix from acoustic waveform belonging to different frequency components in the selected \( t \) and \( v \).
To obtain accurate velocity difference, cross-correlation that avoids the false velocity difference caused by the band-pass filters is effectively used to process the similarity matrix of two adjacent frequency components especially for acoustic data with weak signal-to-noise.

**Algorithm workflow**

- Broadband filtering for the original full-waveform multipole acoustic data (Figure 1). Taking P wave as an example, the similarity matrix filtered becomes more convergent, and the range of \( t \) and \( v \) is more accurate as shown in Figure 1. The velocity of P wave picked up is 7106 m/s, and the one of S wave is 3827 m/s.
- Determining \( t \) and \( v \) range of P wave in the similarity matrix based on STC algorithm for waveform data filtered.
- Applying serial band-pass filters to waveform data filtered by broadband filter in selected \( t \) and \( v \) range, and performing STC algorithm to calculate the similarity matrix in each frequency component. Here, the parameters of these cosine fringed band-pass filters, of which passband width is 4kHz and moving step length is 0.5kHz, are determined by multi-taper tests.
- Calculating the cross-correlation between similarity matrices in two adjacent frequency components to obtain a correlation matrix of which maximum corresponds the velocity difference \( \Delta v_p \) of two frequencies and derives the velocity gradient \( \Delta v_p / \Delta f \) and dispersion increment \( \Delta v_{pf} \) in \( t-v \) domain.
- Searching the characteristic frequency \( f_c \) corresponding to the maximum \( \Delta v_p / \Delta f \), and estimating the inverse quality factor \( Q^{-1} \) by \( \Delta v_p / \Delta f, \Delta v_{pf} \) and \( f_c \).

**Figure 1** Comparison of original full-waveform multipole acoustic data before and after the broadband band-pass filtering. a) The original waveform of the first receiver. b) The filtered waveform. c) The similarity matrix of the original waveform at 3036.7m. d) The similarity matrix of the filtered waveform at 3036.7m.

**Velocity dispersion and attenuation analysis of actual acoustic data**

The velocity dispersion and attenuation of P wave which can be clearly found in whole well especially hydrocarbon layers, are researched to verify the applicability of the frequency-division cross-correlation method based on STC to original full-waveform multipole array acoustic data measured by DSI tool in the carbonate reservoir. According to time-frequency analysis, the parameters of these cosine fringed band-pass filters, of which passband width is 4kHz and moving step length is 0.5kHz, can be determined from 7kHz to 25kHz.

As shown in Figure 2, the velocity gradient and incremental profiles of P wave correspond well to the hydrocarbon layers. The characteristic frequency \( f_c \) moves backward in 5624m-5730m, forward in 5730m-5750m and 5775m-5780m, and shows two peaks in 5800m-5880m and 5900m-5945m. Thus, the \( f_c \) is mainly distributed in two ranges of 17.5kHz-19kHz and 22.5kHz-24kHz. In most depth, the velocity of P wave increases with frequency, but the opposite cases which may be due to scattering in some layers. The inverse quality factor \( Q^{-1} \) is estimated by the constant \( Q \) model (Liu, Anderson and Kanamori, 1976).
Figure 2  
(a) Waveform of the first receiver from DSI tool at 5624m-5945m.  
(b) Velocity gradient profile of P wave with 15kHz-24kHz.  
(c) Velocity dispersion increment profile relative to the velocity of P wave at 15kHz.

In order to illustrate the effectiveness of P wave dispersion and attenuation on fluid identification, the velocity dispersion increment $\Delta v_{pf}$ and inverse quality factor $Q^{-1}$ are compared and analyzed with conventional logging, electric imaging logging and interpretation conclusion as shown in Figure 3.  

In the vuggy layer at 5675m-5730m as shown in blue top box of Figure 3, the borehole diameter expands sharply, the FMI image shows abundant vugs and few fractures, and hydrocarbon saturation $S_h$, $\Delta v_{pf}$ and $Q^{-1}$ have high values. Due to the interpretation result from the oilfield, vugs widely distribute in this layer with best hydrocarbon saturation. Comparing with the velocity gradient and dispersion increment profiles (Figure 2), the velocity dispersion and attenuation caused by the hydrocarbons in vugs correspond to the characteristic frequency $f_c$ (22.5 kHz-24 kHz). In the fractured-vuggy layer at 5826m-5865m as shown in blue bottom boxe of Figure 3, the FMI image shows that the fractures and vugs

Figure 3  
Comprehensive comparative analysis. Depth, caliper curve, FMI image, fracture occurrence, inverse quality factor $Q^{-1}$, velocity dispersion increment of P wave $\Delta v_{pf}$, hydrocarbon saturation $S_h$, porosity curve, deep and shallow resistivity curves display from left to right.

Figure 4  
Crossplot analysis.  
(a) Velocity dispersion increment of P wave $\Delta v_{pf}$ with hydrocarbon saturation $S_h$.  
(b) Inverse quality factor $Q^{-1}$ with hydrocarbon saturation $S_h$.  

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extremely develop and interconnect, which leads to the two $f_c$ in Figure 2. The velocity dispersion and attenuation caused by the hydrocarbons in vugs correspond to $f_c$ (22.5 kHz-24 kHz), and in fractures reflect $f_c$ (17.5kHz-19kHz). According to two crossplots from vuggy and fractured-vuggy layers as shown Figure 4, $\Delta Vpf$ and $Q^{-1}$ appear positive correlation with $S_{hc}$, which indicates that hydrocarbons play major role in the velocity dispersion and attenuation of P wave. It proves that $\Delta Vpf$ and $Q^{-1}$ are effective parameters for quantitative fluid evaluation in carbonate reservoirs especially when hydrocarbon saturation is unavailable.

**Conclusion**

The frequency-division cross-correlation method based on STC provides a new way to calculate velocity dispersion and estimate attenuation from the full-waveform multipole acoustic logging data. Comparing and analyzing of actual logging data, the results demonstrate the effectiveness of the new method on fluid identification in carbonate reservoirs. $\Delta Vpf$ and $Q^{-1}$ acquired can effectively indicate the fluid in the reservoirs. It not only makes up for the inaccurate saturation calculated by the existing logging methods, but also provides the basis for reservoir evaluation. The method has acquired satisfactory precision and robustness for actual data, but is still in the preliminary exploration stage. The next work is to carry out the dispersion extraction and attenuation estimation for S wave and Stoneley wave, so as to identify fluid more accurately.

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**References**


