Fine interpretation by using the VMD-based Instantaneous centroid estimation method for a marine carbonate gas reservoir

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Abstract. We apply the variational mode decomposition (VMD)-based instantaneous centroid estimation method for interpreting a 11-meters main gas-producing interval of the Longmenshan foreland basin, China. Five VMD-based instantaneous centroid slices are generated for fine interpretation. The results are evaluated by the measured well data. The application results show that the VMD-based instantaneous centroid estimation method targets the 11m main gas-producing interval very well. Field data application shows that the VMD-based instantaneous centroid estimation method can give a fine interpretation of hydrocarbon-related information with high-precision.

1. Introduction

The marine strata in the middle part of the Longmenshan foreland basin, China, are deeply buried. At present, the exploration targets and the oil and gas breakthroughs obtained are both in the uppermost Ma’antang formation and Leikoupo formation. Here, we mainly study the marine strata of the Ma’antang formation, Upper Triassic. The Ma'antang formation is the last marine carbonate sedimentary stratum in the Sichuan Basin and the basis for the development of the Longmenshan foreland basin. The unconformity of the weathering crust between the Ma'antang formation and the Leikoupo formation is widely distributed in western Sichuan. Fracturing-porosity reservoirs in beach faces are mainly developed in the Ma’antang formation. The reservoir space is cracks, intergranular (dissolved) pores and intragranular dissolved pores. The porosity of the reservoir is 2.3%~8.5% and the average porosity is 6.3%. The permeability is $0.01 \times 10^{-3} \mu m^2 \sim 12.01 \times 10^{-3} \mu m^2$ and the average permeability is $6.6 \times 10^{-3} \mu m^2$. The seismic response characteristics are weak. The depth of the target layer is about 5,000 meters. The logging data is scarce and there are only three wells named A, B and C in this area. Reservoir prediction and gas-bearing detection are relatively difficult.

Main gas production interval of Well A in Ma'antang formation is about 11 meters. The seismic data is sampled at 2ms. The main gas production interval is very thin and it requires a high-resolution interpretation method for detecting the hydrocarbons-related information. The VMD-based instantaneous centroid estimation method [1] is a newly developed novel hydrocarbon detection technique. It can easily reveal frequency dependent amplitude anomalies that may reflect some details deeply buried within the intrinsic mode functions (IMFs) in particular frequency bands. We apply this
novel VMD-based instantaneous centroid estimation method for fine interpretation of the thin main gas production interval of Well A.

2. Principle and methods
Frequency-dependent amplitude anomaly information is widely used for hydrocarbon detection since seismic wave energies exhibit obvious high-frequency attenuation in or beneath gas-bearing layers [2-3]. Spectral decomposition is commonly used for detecting the frequency-dependent amplitude anomaly information through a series of common frequency volumes [4]. The different response characteristics of geological bodies can be reflected in the different common frequency volumes and hydrocarbon information may be clearly revealed in the common frequency volumes at some certain frequencies. But the workflow of the common spectral technology is complicated since a number of common frequency volumes are required for analysis.

The VMD-based instantaneous centroid estimation method is a novel method for detecting frequency-dependent amplitude anomaly information. It mainly includes the following steps:

1) Decompose the seismic data by variational mode decomposition (VMD) method to obtain the intrinsic mode functions (IMFs) trace by trace. The decomposition parameters such as the decomposition level of VMD, the balancing parameter of the data-fidelity constraint, time-step of the dual ascent, and the tolerance of the convergence criterion need to be determined. Generally, the decomposition parameters such as the balancing parameter of the data-fidelity constraint, time-step of the dual ascent, and the tolerance of the convergence criterion are relatively easy to determine. But the decomposition level of VMD, that is, the number of IMFs generated by the VMD is difficult to determine. Here, we use an empirical formula for determining the decomposition level of VMD [1]:

$$k = \frac{f_s / f_d}{\log(M)},$$  \hspace{1cm} (1)

where $f_s$ is the sampling frequency, $f_d$ is the dominant frequency of each seismic trace, $M$ is the length of each seismic trace, and $[\cdot]$ denotes a rounding up operation.

2) Calculate the instantaneous attributes of the IMFs for each seismic trace. For an IMF $u(t)$ obtained by VMD for a seismic trace, its instantaneous amplitude $A(t)$, instantaneous phase $\phi(t)$ and instantaneous frequency $f(t)$ can be calculated by the following equation (2):

$$A(t) = \sqrt{u^2(t) + y^2(t)}$$

$$\phi(t) = \arctan\left(\frac{y(t)}{u(t)}\right),$$

$$f(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt},$$

where $y(t) = H[u(t)] = \frac{1}{\pi} P\int_{-\infty}^{\infty} \frac{u(\tau)}{t-\tau} d\tau$, $H[\cdot]$ denotes the Hilbert transform. $P$ is the Cauchy main value.

Generally, the instantaneous frequency $f(t)$ is computed by the equation (3) to avoid ambiguities caused by phase unwrapping in equation (2).

$$f(t) = \frac{1}{2\pi} \frac{dy(t)}{dt} - \frac{\dot{y}(t)}{\dot{u}(t) + y(t)} \frac{da(t)}{dt},$$

3) Calculate the instantaneous centroid of each seismic trace. For a seismic signal, the instantaneous centroid $c_i$ calculated by each IMF is first calculated. Then, the correlation weighting coefficient is used for the instantaneous centroid of each IMF to generate the final instantaneous centroid $C$ of the seismic trace:

$$C = \sum_{i=1}^{N} R_i \cdot c_i.$$
\[ c_i = \frac{f_A A_i}{\sum A_i}, \]

where \( k = 1, 2, \ldots, N \), \( N \) is the number of IMFs. \( f_i \) is the instantaneous frequency of the IMF at each time sample. \( A_i \) is the instantaneous amplitude of the IMF at each time sample. Instantaneous centroid \( C \) can reflect frequency anomaly information more effectively.

Here, the weighted correlation scheme is employed to generate the VMD-based instantaneous centroid volume for a seismic trace:

\[ R_c = \begin{cases} 1, & |R| \geq 0.3 \\ 10^{-1}, & 0.1 \leq |R| < 0.3 \\ 10^{-3}, & |R| \leq 0.1 \end{cases} \]

where \( R \) represents correlation coefficient.

This operation is mainly to keep the instantaneous centroid calculated by the strong-correlated IMFs unchanged and attenuate the instantaneous centroid calculated by the weak-correlated IMFs for enhancing the main contributor of the seismic trace. The final calculated instantaneous centroid volume for a seismic trace is always normalized to the interval range \([0, 1]\).

4) The instantaneous centroid volumes of the entire seismic data is calculated trace by trace.

The VMD-based instantaneous centroid estimation is more convenience when compared with the conventional spectral decomposition methods. It is also an attenuation estimation method with high-precision.

3. Field data applications

For interpreting the main gas production interval of Well A in Ma'antang formation, we apply the VMD-based instantaneous centroid estimation method to the 3D broadband stacked migrated seismic data. Since the main gas production interval of Well A in Ma'antang formation is about 11ms and the seismic data is sampled at 2ms, we mainly extract the VMD-based instantaneous centroid slices at downward 2ms, 4ms, 6ms, 8ms and 10ms from the top of the Ma'antang formation for fine interpretation. The corresponding VMD-based instantaneous centroid slices are shown in Figure 1.

According to the logging data, at downward 2ms from the top of the Ma’antang formation, the well B (about 5702m) is in layer with gas and water. There is no gas display for the well A (about 5620m) and the well C (about 5514m). The results obtained in Figure 1a are consistent with the measured well data.

According to the logging data, at downward 4ms from the top of the Ma’antang formation, the well B (about 5707m) is a gas-bearing layer; the well A (about 5625m) has entered the main gas-producing zone (5622m-5636m); There is still no gas layer existed for the well C (about 5519m). Figure 1b gives a similar interpretation results which show a consistence with the measured well data.

According to the logging data, at downward 6ms from the top of the Ma’antang formation, a gas-water layer exists for the well B (about 5713m); the well A (about 5631m) is still located in the main gas-producing interval (5622m-5636m); the well C (about 5525m) still shows no gas layer. The processing results shown in Figure 1c are consistent with the measured well data.

According to the logging data, at downward 8ms from the top of the Ma’antang formation, the well B (about 5718m) is at the water layer; the well A (about 5636m) is still in the main gas production interval (5622m-5636m); There is still no gas layer existed for the well C (about 5531m). The results shown in Figure 1d are consistent with the measured well data.

According to the logging data, at downward 10ms from the top of the Ma’antang formation, the well B (about 5723m) is at the water layer; the well A (about 5642m) is out of the main gas production interval (5622m-5636m); There is still no gas layer existed for the well C (about 5537m). The results shown in Figure 1e are consistent with the measured well data.

In summary, it can be seen from Figure 1a-1e that the VMD-based instantaneous centroid estimation method accurately identifies the main gas-producing interval of the well A. The hydrocarbon response characteristics of the gas-producing interval is from downward 4 meters to 8
meters from the top of the Ma’antang formation, and the interpreted thickness is about 11 meters. The thickness and depth are consistent with the measured well data. The hydrocarbon response characteristics of the other two wells are also consistent with their logging data. Field data application shows the VMD-based instantaneous centroid estimation method can effectively target gas reservoirs and give the fine interpretations for hydrocarbon-related information.

![Image](image_url)

**Figure 1.** The VMD-based instantaneous centroid slices at the target layer for the seismic volume. (a) slice at downward 2ms from the top of the Ma’antang formation. (b) slice at downward 4ms from the top of the Ma’antang formation. (c) slice at downward 6ms from the top of the Ma’antang formation. (d) slice at downward 8ms from the top of the Ma’antang formation. (e) slice at downward 10ms from the top of the Ma’antang formation.

4. Conclusions
We apply the VMD-based instantaneous centroid estimation method to interpret a thin main gas-producing interval of the Longmenshan foreland basin, China. According to the thickness of the main gas-producing interval of Well A, we generate five VMD-based instantaneous centroid slices to show the fine hydrocarbon response characteristics of the gas-producing interval of Well A. The results obtained by the VMD-based instantaneous centroid estimation method are consistent with the measured well data and give a result that the main gas-producing interval is about 11m. Field data application results show that the application of the VMD-based instantaneous centroid estimation method can give a fine interpretation of hydrocarbon-related information.

Acknowledgments
This work was supported in part by the National Natural Science Foundation of China under Grants 41404102, 41430323, and 41674112, in part by the National Science and Technology Major Project under Grant 2016ZX05024-005-007 and 2017ZX05072002-003, in part by the Sichuan Youth Science and Technology Foundation under Grant 2016JQ0012. The authors also thank for the support of SINOPEC Key Laboratory of Geophysics.
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