The application of frequency-dependent AVO inversion in tight reservoirs area
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Summary

Fluid-saturated rocks are generally expected to have frequency-dependent velocities, and it is attractive to try to use this property to discriminate different fluids with seismic data. When the reservoirs are saturated with different fluid types, the magnitude of dispersion is different. In this paper, the frequency-dependent AVO inversion method is combined with the technology of Smoothed Pseudo Wigner-Ville Distribution (SPWVD), which is used for spectral decomposition intended to get the excellent time-frequency localization. We use SPWVD for spectrally decomposing post-stack seismic data to find the frequency anomalies, pre-stack CMP gathers at the location of these frequency anomalies are extracted for frequency-dependent AVO inversion. Compared the identical frequency profiles of post-stack data with the result of inversion on pre-stack data, we can eliminate the high amplitude energy group caused by elastic interfaces and reserve the dispersion anomalies resulted from dispersive interfaces. The real seismic example from XN gas field of Sichuan basin, southwest of China, proved that this method is effective in discriminating gas and water in tight reservoirs.

Introduction

Studies suggest that modern spectral decomposition has been applied as another instrument for direct hydrocarbon indicators (DHI) based on the frequency of seismic reflections (Castagna et al., 2003). When gas is saturated, unlike the case of water, the magnitude of dispersion increases sharply through numerical modeling (Chapman et al., 2006). At the peak frequency, the amplitude difference of the reservoirs saturated with gas and water is the maximum (Ren et al., 2007). Wilson et al. (2009) introduced a frequency-dependent AVO inversion algorithm, intending to obtain the magnitude of dispersion directly from pre-stack data. The method based on Smith and Gidlow’s (1987) two-term AVO approximation. Wu et al. (2010) introduced a high-resolution spectral decomposition method-SPWVD, and further applied on real seismic data of North Sea. Sam et al. (2014) derived three-term frequency-dependent AVO inversion algorithm and achieved good results in carbonate reservoirs.

In this paper, we have demonstrated the application of frequency-dependent AVO inversion to real seismic data using Smoothed Pseudo Wigner-Ville distribution for spectral decomposition. The results of the second member of Xujiahe Formation (TX2) in XN gas field prove that the magnitude of P-wave dispersion can identify fluid in tight reservoirs. Combined with drilling information, we can identify the horizontal distribution features and connectivity of fluid.

Theory

Frequency-dependent AVO is to promote and expand the conventional method. That is seen the velocities of seismic wave as a function of frequency. So that the Smith and Gidlow’s two-term AVO approximation expresses can be written as:

\[ R(\theta, f) \approx A(\theta) \frac{\Delta V_p}{V_p} (f) + B(\theta) \frac{\Delta V_s}{V_s} (f) \]  

in which \( \theta \) is the angle of incidence, \( A \) and \( B \) can be derived in terms of the velocities and the angle of incidence. Expanding equation (1) as first-order Taylor series at a reference frequency \( f_0 \) (Wilson et al., 2009):

\[ R(\theta, f) \approx A(\theta) \frac{\Delta V_p}{V_p} (f_0) + (f - f_0) A(\theta) I_a \]

\[ + B(\theta) \frac{\Delta V_s}{V_s} (f_0) + (f - f_0) B(\theta) I_b \]  

(2)

Where \( I_a \) and \( I_b \) are the derivatives of impedance with respect to frequency evaluated at \( f_0 \):

\[ I_a = \frac{d}{df} \left| \frac{\Delta V_p}{V_p} \right|_{f=f_0} \]

\[ I_b = \frac{d}{df} \left| \frac{\Delta V_s}{V_s} \right|_{f=f_0} \]  

(3)

For a typical CMP gather with \( n \) receivers denoted as a data matrix \( S(t, n) \). Coefficients \( A \) and \( B \) at each sampling point can be obtained with the knowledge of velocity model through ray tracing denoted as \( A_n(t) \) and \( B_n(t) \). We perform SPWVD on \( S(t, n, f) \) and get the spectral amplitude \( S(t, n, f) \) at a series of frequencies. Then use the reference frequency to do spectral balance. So that the equation (2) expands to a matrix equation, which can be solved by the least squares method to obtain \( I_a \) and \( I_b \).
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Application

The objective reservoirs is the upper and the middle part of TX2, which have features of large depth, low permeability, and poor porosity. Therefore, the high productivity of gas depends on the distribution of fractures in XN gas field. It is a delta-front to pro-delta sedimentary environment, where sandstone and mudstone are interbedded sedimentary with unequal thickness, in which the sandstone obviously dominant. At the same time, the characteristics of stratigraphic cycle are not obvious and the delineation and horizontal distribution of sandstone are very complicated, so that the conventional method of inversion in this region is difficult to obtain accurate results. To solve the problems, we try to use the frequency-dependent AVO inversion.

In this part, we combine spectral decomposition of post-stack data and frequency-dependent AVO inversion on pre-stack data using SPWVD. Figure 1 display the workflow of frequency-dependent AVO inversion on real seismic data. First of all, we use spectral decomposition of SPWVD on post-stack data to get a series of identical frequency sections. Then selecting the frequency corresponding to the maximum amplitude spectrum of a known elastic interface as reference frequency, we use the profile to do spectral balance on other identical frequency sections. After that, we analyze the variation characteristics of amplitude spectra and find the frequency anomalies related to fluids saturation. Finally, we extract the pre-stack CMP gathers at the position of the frequency anomalies for frequency dependent AVO inversion for quantitative description of dispersion.

We select a seismic profile of inline1548 from XN. Through spectral analysis of post-stack and pre-stack seismic data, we know that the dominant frequency for both post-stack and pre-stack data is around 20Hz with bandwidth from 0Hz to 50Hz for per-stack data and 5Hz to 50Hz for stacked data. Then post-stack identical frequency profiles at 10Hz, 20Hz, 30Hz, and 40Hz are obtained by SPWVD. The horizon T51 is the top of the second sand group (TX2) and T511 is the top of the forth sand group (TX4). Figure 2(a) shows the post-stack profile of inline1548 and three “bright spots” labelled as NO.1, NO.2 and NO.3. Figure 2(b-e) displays the spectra at different frequencies after spectral balance with 20Hz as reference frequency. We can see that spectral amplitudes at NO.1 and NO.2 decrease with frequencies, whilst the NO.3 has small changes with frequencies.
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In order to determine whether the bright spots is caused by gas or water, we select the traces of 1280-1540 CMP gathers from Inline1548 to do frequency-dependent AVO inversion. To satisfy the assumptions of Smith and Gidlow’s two-term AVO approximation formula, we analyze the incidence angle distribution of one CMP gather by the method of ray tracing. Figure 3 displays the incidence angle distribution of NO. 1320 CMP gather. Obviously the incidence angles under 1s are smaller than 30 degrees except for the traces after NO. 40 trace. So that we select first 45 traces of every CMP gather to join in inversion calculation.

We eventually perform SPWVD on all selected pre-stack CMP gathers to obtain identical frequency sections at 10, 20, 30, 40 and 50Hz and conducted spectral balance with 20Hz as reference frequency. Figure 4 display the inversion result of magnitude of P-wave dispersion of inline1548. Compared with the identical frequency sections of post-stack data, we can see that we have got rid of strong energy clusters caused by elastic interface at about 1.6s to 1.8s and reserved the anomalies result from dispersion.

Fortunately, this profile passes through two wells are displayed on figure 4. The one is N6, and the other is N3. For N6 well, TX$_2^2$ corresponding to the large magnitude of P-wave dispersion is interpreted into gas reservoirs from logging data, and TX$_2^2$ is interpreted into gas-bearing sandstone, corresponding to the middle magnitude of dispersion. For well of N3, the main gas reservoirs is TX$_2^2$ corresponding to middle to large dispersion. Thence, we can interpret the large magnitude of P-wave dispersion around No.1 and No.2 anomalies into gas reservoirs. While the small magnitude of P-wave dispersion around No.3 anomaly is resulted from region of saturated water. In addition, we can safely draw the conclusion that the magnitude of P-wave dispersion is positively correlated with the gas production.

Figure 2: Post-stack section of inline1548 and its spectra at different frequencies.

Figure 3: Incidence angle of No. 1320 CMP gather.
**Conclusion**

In this paper, we have applied the frequency-dependent AVO inversion on tight reservoirs to distinguish the types of fluid, which results agree well with drilling information. We found that the horizontal distribution features of the large dispersion are similar to sandstone and the magnitude of P-wave dispersion is positively correlated with the gas production. The application of the real data illustrate that this approach is effective in tight clastic area. However, it must be emphasized that this method is only applicable on near-offset data.

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