Estimation of fluid mobility from frequency dependent azimuthal AVO – a synthetic model study

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Summary

Azimuthal amplitude-versus-offset (AVOZ) data can contain abundant information on fracture properties, lithology and fluid saturation, but procedures for interpretation in terms of such properties remain relatively poorly developed, particularly considering the frequency dependent content. In our numerical model, we developed recently developed rock physics model based inverse schemes with a particular emphasis on accounting for the frequency-dependence of anisotropy, which is believed to be important in fractured reservoirs. Frequency-dependent anisotropy is expected to be influenced by fluid mobility, and determining this parameter from seismic data would be advantageous. In this paper we build a frequency dependent anisotropic synthetic model and show the variations of AVO response due to frequency effects. We present a new method to analyse the synthetic waveform data, and demonstrate that it is capable of detecting variations in fluid mobility. Further testing and application to field data are planned.
Introduction

Azimuthal variations of AVO data (AVOZ) have been widely used to detect fractures for some time. While the link to fractures is clear, additional parameters (porosity, fluid content and lithology) also are known theoretically to have an important influence. Qualitative interpretation of AVOZ, by contrast, typically relies on simple techniques (ellipse fitting of attributes), justified by simplified anisotropic rock physics models. There is an indeed need to involve more detailed rock physics models in the quantitative interpretation of AVOZ data.

Motivated by the work of Reide et al. (2005), Varela et al. (2009) introduced a rock physics model based method for the estimation of fracture density from AVOZ. Maultzsch et al. (2003) demonstrated a number of examples of frequency-dependent anisotropy in fractured reservoirs which lead us to target other properties. Ren et al. (2013) extend the Varela et al. (2009) method to the case of fluid mobility which is considered to play an important role in controlling frequency-dependent properties (Batzle et al., 2006) and whose determination would clearly be very important.

In this paper, we build a synthetic model within a HTI layer derived by Chapman (2003) frequency dependent rock physics model. Spectral decomposition and balancing technique are applied to obtain frequency content of amplitudes. We use SVD to analyze the amplitudes. The frequency dependent fluid mobility of HTI layer (Class 2 AVO) can be quantitatively interpreted. We argue that in certain cases it may be possible to obtain fluid mobility information from AVOZ data.

Building synthetic model

Figure 1a shows the layout and geometry of the model (in the XZ plane). From top to bottom there are four layers, which are two isotropic, anisotropic and isotropic in order. The P- and S-wave velocities, density and thickness of each layer are embedded within relating layers. The material of the anisotropic layer is a set of vertical fractures with fracture density of 0.1. In this study, I will analyse the reflection from 2nd interface between the isotropic layer 2 and the underlying HTI layer 3. The seismic amplitude of 2nd interface is calculated by using Chapman (2003) fluid induced frequency dependent anisotropic rock physics model. In this model, a relaxation timescale parameter \( \tau \) which depends on fluid viscosity and permeability was introduced to control the frequency range over which the attenuation and dispersion occurs. The focus on this paper is determining \( \tau \) from waveform data.

Figure 1b shows the seismic profile containing only Z-component of this synthetic model. The 1st and 2nd P-wave reflections which we are interested are highlighted. The S-wave, PS-wave and some noise can be removed during processing. NMO correction is applied on these two reflections and the result is illustrated in Figure 2. The waveform data can be created with a set of \( \tau \) and azimuth angles. However, to obtain frequency dependent reflection coefficients, Spectral decomposition technique is desired.

Spectral decomposition and balancing

Spectral decomposition is a technique for deriving the frequency content of a signal. Fourier transform can give the overall frequency behavior of a signal, however it is inadequate for analyzing a non-stationary signal (Seismic signals are non-stationary due to absorption and attenuation of energy). Cohen (1995) introduced short-time Fourier transform (STFT) by taking short segments of the signal and then performing the Fourier transform on the windowed data to obtain local frequency information. The signal, \( f(t) \), can be transformed by a time-shifted window function, \( \phi(t) \), as

\[
STFT(\omega, t_0) = \int_{-\infty}^{\infty} f(t)\phi(t - t_0)e^{-i\omega t} dt
\]

Where \( t_0 \) is the translation time, \( \omega \) is the frequency. STFT is widely used in seismic interpretation. In Figure 3, we can see that the spectral amplitudes of the first reflection with different frequency domain have significant difference which is not supposed to happen when it is elastic, because the spectral amplitudes have an overprint from the source wavelet (Partyka et al., 1999).

Wilson et al. (2009) derived a method to remove the effect of the source wavelet by a weight function, \( w(f) \), making the amplitudes at different frequencies comparable. When working with synthetic data, the top two layers are elastic so that the 1st reflection is elastic. These elastic reflections are used to
derive weights that automatically balance deeper spectral amplitudes. Note that, considering the trace dependent NMO stretch, I calculated the weights trace by trace. Wilson’s equation can be derived as

\[ B(t, n, f) = S(t, n, f)w(n, f) \]  

Balanced spectral amplitudes are displayed in Figure 4, in which we can see the similar response of the 1st interface but difference of the 2nd reflection by frequency.

**Singular value decomposition (SVD)**

In our synthetic model, we study the plane wave amplitude at second reflection. The lower layer is assumed to be anisotropic and to have frequency dependent properties. The balanced spectral amplitude, considering as reflection coefficient, can be constructed into a matrix varying with a discrete number of incidence angles (\( \theta \)), azimuths (\( \phi \)), relaxation timescale parameters (\( \tau \)) and frequencies (\( f \)). Alternatively, considering a single frequency we can write:

\[ R = \begin{bmatrix} R_{\theta_1, \phi_1} & \ldots & R_{\theta_1, \phi_\phi} & \ldots & R_{\theta_1, \phi_\phi} & \ldots & R_{\theta_1, \phi_\phi} \\ R_{\theta_2, \phi_1} & \ldots & R_{\theta_2, \phi_\phi} & \ldots & R_{\theta_2, \phi_\phi} & \ldots & R_{\theta_2, \phi_\phi} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ R_{\theta_n, \phi_1} & \ldots & R_{\theta_n, \phi_\phi} & \ldots & R_{\theta_n, \phi_\phi} & \ldots & R_{\theta_n, \phi_\phi} \end{bmatrix} \]  

(3)

Singular value decomposition (SVD) can be applied to this matrix in the usual way giving a representation:

\[ R = FDV^T = FW \]  

(4)

Applying SVD and multiplying the decomposed matrices allows us to obtain the approximation to the reflection coefficient as:

\[ R(\theta, \phi, \tau) \approx C_1(\phi, \tau)F_1(\theta) + C_2(\phi, \tau)F_2(\theta) + \ldots \]  

(5)

where the basis functions \( F_i(\theta) \) are given by the columns of matrix \( F \), the coefficients \( C_i(\omega, \tau) \) are given by the columns of the weight matrix \( W \), size of which is corresponding to the singular value of matrix \( D \). Usually we only need to consider two or three terms of approximation in practice with small error (Riede et al., 2005).

**Results**

In synthetic model we find that the reflection coefficient is well approximated with the use of only the 1st order basis function. The reflection coefficient can therefore be approximated from Equation 5 as:

\[ R(\theta, \phi, \tau) = C_1(\phi, \tau)F_1(\theta) \]  

(6)

The coefficients \( C_i(\omega, \tau) \) variation with \( \phi \) and \( \tau \) can be presented in Figure 5. In order to obtain the approximation attributes of the coefficients \( C_i(\omega, \tau) \), a cosine fitting is applied on these datasets (Figure 5), which is assumed to follow the equation:

\[ y = C + \alpha \cos(\phi) + \beta \cos(2\phi) + \gamma \cos(3\phi) \]  

(7)

There are four attributes \( C, \alpha, \beta \) and \( \gamma \), in which according to this model, all attributes depend on frequency. The second attribute \( \alpha \) has the most direct dependence on \( \tau \). We also notice that, compared with the value of \( C \) and \( \alpha, \beta \) and \( \gamma \) can be neglect. We can cross-plot \( C \) and \( \alpha \) respectively for each frequency, and apply polynomial fitting method to the result (Figure 6). Cross-plotting these attributes for each frequency gives rise to a “template” which allows us to see clearly the effect of changing values of the frequency or \( \tau \) (Figure 6).

**Conclusions**

This paper has carried out a synthetic model in which we found that fluid-mobility does have an impact on azimuthal AVO, particularly if we consider variations with frequency. To obtain appropriate seismic amplitudes, spectral decomposition and spectral balancing technique are applied. To analyze the amplitudes variations, link to all dependent parameters, we applied our numerical
method. From the synthetic model study, we have successfully validated we can derived a template showing the variation of fluid mobility from waveform data. Further testing and application on field data will be carried out.

References


Figure 1 a. Four layers synthetic model. The rock properties are embedded within the geometry. b. Seismic profile of this model. The 1st and 2nd P-wave reflections are highlighted in the figure.

Figure 2 NMO corrections of the top two reflections when $\tau = 2e - 4$. a. P-wave propagates perpendicular to the direction of fractures ($\phi = 0^\circ$). b. P-wave propagates parallel to the direction of fractures ($\phi = 90^\circ$). For the 2nd interface, amplitude at far offsets of $\phi = 0^\circ$ are larger than that of $\phi = 90^\circ$ illustrate more significant anisotropy.
Figure 3 Spectral decomposition slices of the top two reflections when $\tau = 2e^{-4}$, $\varphi = 0^\circ$. a and b are spectral decomposition; c and d are spectral balancing. a. 10Hz slice. b. 50Hz slice. There is significant difference of the 1st reflection between different frequency which is not supposed to be. These two slices are incomparable unless processed with spectral balancing.

Figure 4 Spectral balanced amplitude from spectral decomposition (Figure 3). a. 10Hz slice. b. 50Hz slice. The 1st reflections of difference frequency are similar but significant difference at 2nd reflections due to fluid induced anisotropy (Chapman, 2003).

Figure 5 Weights variation with azimuth angle and $\tau$. *shows data calculated from study model. Solid line is cosine fitting curve. Color relates to different $\tau$.

Figure 6 Frequency dependent fluid property $\tau$ template. The spots are derived from the cross-plot of two attributes. The colored solid lines illustrate frequency variation. The colored dash lines refers to different $\tau$. 