Use of frequency dependent AVO inversion to estimate P-wave dispersion properties from reflection data

Authors

A. Wilson, M. Chapman & X-Y. Li

Summary

It has recently been suggested that fluid-sensitive dispersion can give rise to a frequency-dependent AVO response, and that the ability to detect such an effect could in principle help us to detect hydrocarbons. In this paper we develop an algorithm which allows us to estimate P-wave dispersion properties from reflection data. We begin by performing spectral decomposition on our pre-stack data, and perform balancing to remove the overprint of the wavelet. Under the assumption that the impedance contrast is a function of frequency, we develop a linearised AVO approximation for the frequency-dependent case. A Smith-Gidlow style inversion applied to the spectrally decomposed data allows us in principle to recover the variation of impedance contrast with frequency. We test the method on synthetic data, produced from both elastic and dispersive modelling, and find we can recover information on the dispersion properties. We feel our method may complement attempts to measure seismic attenuation from reflection data.
**Introduction**

In this paper we have developed an algorithm for detecting spectral anomalies that are often associated with hydrocarbons via inversion of iso-frequency data. The goal of the study is to be able to quantitatively infer P-wave dispersion properties from analysis of reflection data. Such an analysis will complement efforts to measure attenuation from reflection data.

The advances in the application of spectral decomposition in reservoir characterisation since Partyka et al. (1999) have led to many recorded examples of spectral anomalies in seismic data. Many of these are linked to hydrocarbon reservoirs; Castagna et al. (2003) showed examples of low-frequency shadows using instantaneous spectral analysis. Chapman et al. (2006) showed how equivalent medium theory can model large levels of attenuation and dispersion in hydrocarbon saturated rocks and showed how this gave rise to a frequency-dependent AVO response. Much work utilising spectral decomposition as a fluid indicator has been rather qualitative and there has yet to be a quantitative assessment of frequency-dependent AVO.

This paper shows how a frequency-dependent AVO analysis can be applied to reflection data. We have developed a new workflow to invert the data for a quantitative measure of dispersion. Our method is a generalisation of the Smith and Gidlow (1987) inversion scheme to multiple frequencies. We have tested our method on synthetic data calculated using both elastic and dispersive models. Our study suggests that information on dispersion properties can be recovered from the data, and this offers a promising method to detect areas of hydrocarbon saturation.

**Theory**

We extend the two-term Smith and Gidlow (1987) $\hat{\Phi}$ approximation to include frequency-dependence. When we do this we make no assumption on either the P- or S-wave dispersion, despite theoretical prediction that the S-wave dispersion will be much less than for the P-wave dispersion (as in Chapman et al. (2006)). We take the original approximation, as shown in equation (1):

$$R(\theta) = A(\theta) \frac{\Delta \alpha}{\alpha} + B(\theta) \frac{\Delta \beta}{\beta}$$  

and extend it to include frequency dependence, as shown in equation (2):

$$R(\theta, f) - A(\theta) \frac{\Delta \alpha}{\alpha} \left( \frac{f}{\theta} \right) + (f - \theta) A(\theta) l_\alpha + B(\theta) \frac{\Delta \beta}{\beta} \left( \frac{f}{\theta} \right) + (f - \theta) B(\theta) l_\beta$$

where $l_\alpha = \frac{\Delta \alpha}{\alpha}$ and $l_\beta = \frac{\Delta \beta}{\beta}$. In standard AVO, $A(\theta) = \frac{\beta}{\varepsilon} \left( \frac{\varepsilon}{\mu} \right) \sin^2 \theta_1 + \frac{1}{2} \tan^2 \theta_1$ and $B(\theta) = -\frac{4}{3} \left( \frac{\varepsilon}{\mu} \right) \sin 2 \theta_1$ are offset dependent variables that approximate the reflection amplitude on the seismic trace. In our case we are not using seismic amplitudes but iso-frequency amplitudes, in order to be compare amplitudes at different frequencies the traces must be balanced. We use multiple frequencies so a gather decomposed at frequency $= f$, $B(\theta, f)$ describes the iso-frequency amplitudes after balancing that are approximated in equation (2).

The amplitudes on the iso-frequency gathers are balanced on an offset-by-offset basis from a shallow, elastic-elastic interface. We scale the maximum values for the elastic reflection on the iso-frequency gathers to the amplitude of the 40Hz trace (we used a 40Hz ricker wavelet
as our source). Figure 1 shows the unbalanced (a) and the balanced (b) first traces from the iso-frequency gathers (10, 20, 25, 30, 40, 60 and 80Hz) produced from the elastic synthetic. The shallow elastic reflection at ~0.73s is mathematically balanced in 1b) and this process automatically balances the deeper, elastic, reflection at ~0.85s. It is only after balancing the iso-frequency traces that a comparison of the amplitudes along with the inversion can be carried out.

When we are inverting for dispersion we do not need to input the seismic amplitudes, only the balanced iso-frequency traces. The exact densities, P- and S-wave layer velocities are also input into the inversion. To calculate the angle of incidence we use a straight ray approximation rather than calculate the exact angles through ray-tracing. The small offsets are such that the differences between the exact answer and the approximation are small.

![Figure 1: a) The unbalanced iso-frequency first traces (red-10, green-20, magenta-25, blue-30, black-40, cyan-60 and yellow-80Hz) from the elastic, three-layer, synthetic. b) After balancing the first reflection, the deeper reflection has also been balanced.](image)

**Example: 1D Synthetic Surface Seismic**

We have created two, three-layer, synthetic gathers using a commercially available reflection code (Aniseis) that allows the use of fluid-sensitive frequency-dependent velocities in the model building. Each synthetic gather had traces at offsets 0, 150 and 300m, limiting the potential for NMO stretch in our spectra. The top-two layers are elastic and it is this top reflection that is used in the balancing described above. The bottom half-space was elastic in one synthetic and dispersive in the other; this is achieved by changing a time-scale parameter $\tau$ according to Chapman et al. (2006). In the dispersive half-space, the P-wave velocity increases with frequency within the seismic bandwidth. This results in larger reflection coefficients at increasing frequency as we go from a low to a high impedance medium (Class I). We see this effect on figure 2b). The unbalanced and balanced dispersive iso-frequency first-traces are shown in figure 2. The influence of dispersion is clearly visible in 2b) after balancing has been carried out. The low frequency (10Hz) red line in figure 2b) lies at approximately the same magnitude as in figure 1b) and the dispersion has increased the amplitudes of the reflection coefficient at higher frequencies.

We used a wavelet transform with a Gaussian wavelet to carry out the spectral decomposition. It offers a good balance between computing time and amplitude resolution but does unfortunately have relatively poor temporal resolution. There is significant ‘false’ energy, noise, introduced in figure 1 and 2 between the two reflections and is worst at the lower frequencies.
Figure 2: a) The unbalanced iso-frequency first traces (red-10, green-20, magenta-25, blue-30, black-40, cyan-60 and yellow-80Hz) from the dispersive synthetic. b) After balancing the first reflection has been balanced and the second reflection shows the dispersion with the higher frequencies having the highest amplitudes in agreement with theory.

Results

We have calculated the spectral ratio for all offsets on both synthetics (figure 3 shows the first-trace ratios) as another interpretational step. For the elastic case, figure 3a), we obtain a flat, straight line over ~15-95Hz; in agreement with theory. For the dispersive case, figure 3b), we again have a straight line over the same bandwidth as before but with a positive gradient. This is due to the dispersive half-space at the reflecting boundary; the frequency-dependent reflection coefficient has boosted the amplitudes at higher frequencies affecting the spectral ratio. There is no attenuation in the dispersive case since the seismic wave doesn’t propagate through the dispersive layer, this is an instantaneous effect related to the frequency-dependent AVO.

Figure 3: Spectral ratio of the first trace from the elastic (a) and dispersive (b) synthetic. In the elastic case the ratio is flat whilst in the dispersive case the gradient is positive (indicating a negative Q) that is a result of the increasing reflection coefficient with greater frequency.

After examination of the balanced iso-frequency data (see figures 1 and 2) both synthetics were inverted using the frequencies 25, 30, 40, 60 and 80Hz. These two lowest frequencies (10 and 20Hz) were not included in the inversion because they were deemed to be under an acceptable threshold. This output from the elastic case is our null signature that we compare the dispersive output to. In figure 4b) the second peak at ~0.85s is larger than the peak at the elastic reflection at ~0.73s.
Conclusions

We have developed an algorithm that extends Smith and Gidlow’s (1987) two-term approximation to the frequency-dependent case and have been able to invert for P-wave dispersion properties. Such dispersion anomalies can be due to hydrocarbon saturation. We have tested our algorithm and workflow on two synthetic data sets. The first dataset was created with elastic modelling whilst for the second dataset we included dispersion in the calculation. We have been able to detect a clear difference in signatures between the two cases. We believe this approach offers a novel approach to utilising spectrally decomposed data and can be incorporated in a fully frequency-dependent AVO analysis of seismic data. Whereas in standard AVO analysis multiple, and long, offsets are preferred we can invert for the frequency response, in principle with only one offset. Multiple offsets can stabilise the inversion but could introduce NMO stretch effects at longer offsets. We believe this approach can be a useful tool in hydrocarbon exploration as it can be used on seismic datasets to identify areas of dispersion that are commonly related to oil and gas deposits.

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References


