The Direct Inversion of λ/μ from Elastic Impedance

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Abstract: Elastic impedance (EI) contains valuable information that can be used in reservoir rock as fluid and lithology identification. To get more understanding about the reservoir properties, EI can be reformulated according to the Gray's approximation, in which lamé parameters and density can be successfully extracted. λ/μ, the most sensitive parameter to variations in rocks properties going from shale to gas sand, is often derived indirectly from lamé parameters. On real seismic data often affected by noises, However, This procedure may poses the numerical computation that can introduce cumulative errors in the inverted results. To avoid these ambiguities, the gray's approximation is reformulated introducing the ratio λ/μ. the application of this equation to synthetic and real data show that the inverted results are more stable and less ambiguous than that from conventional procedure, and thus can recover reservoir information very well.

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1. Introduction

The variation of amplitude with offset (AVO) is a powerful tool to distinguish rocks containing gas and oil. From the most popular approximation of the Zoeppritz equations, Gray et al (1999), proposed the new equations expressing the change in AVO in terms of the fundamental elastic rock properties (bulk modulus, lamé modulus and shear modulus). So far there are several approximations of PP reflection coefficient that are often used in AVO analysis and inversion (Castagna, 1994, Gray, 2000). Due to the wavelet variation with offset which requires a special correction (wavelet stretching correction) in order to perform AVO inversion, it has recently become popular to perform elastic impedance inversion (Cambois, 2000) and extract the elastic parameters from the EI. Following the same derivation procedure proposed by Connolly (1998), Wang et al (2008) derived the new elastic impedance in terms of lamé parameters and density, and thus inverted lamé parameters and density from this EI .laboratories measurements shown that the moduli ratio, λ/μ are by far the most sensitive parameter to variations in rocks properties going from shale to gas sand (Goodway, 1997) .Since today, the moduli ratio λ/μ is always computed indirectly after the inversion of lamé parameters. On real seismic data often affected by noises, However, This procedure may poses the numerical computation that can introduce cumulative errors in the inverted results. To avoid this ambiguity, the gray's approximation is reformulated introducing the parameter λ/μ.

Using the same derivation procedure as in Connolly (1998), the new elastic impedance in terms of the ratio moduli λ/μ, lame's modulus, and density is derived, the application of this equation to synthetic and real data show that the inverted results are more stable and less ambiguous than that from conventional procedure, and thus can recover reservoir information very well.

2. Material and Methods

2.0 Methods

2.1 Gray approximation and its reformulation

From the well known linearization of the Zoeppritz equations for P-wave reflectivity, introduced by Aki and Richard (1980), Gray et al (1999) proposed an approximation in terms of lamé parameters and density.

$$R_{PP}(\theta) = \frac{\sec^2\theta}{4}\left[1 - 2\left(\frac{\beta}{\alpha}\right)^2\right]\frac{\Delta\lambda}{\lambda} + \left(\frac{\beta}{\alpha}\right)^2\left[\frac{\sec^2\theta}{2} - 2\sin^2\theta\right]\frac{\Delta\mu}{\mu} + \frac{1}{4}\left[1 - \tan^2\theta\right]\frac{\Delta\rho}{\rho} \tag{1}$$

Where R is the reflectivity at the incidence angle θ, λ, μ and ρ are the Lamé constant, the shear modulus and the density, respectively.

The formula above has an advantage over previous linearization of the Zoeppritz equations in fact that the fundamental elastic rock properties (bulk modulus, lamé modulus and shear modulus) can be inverted directly (Gray, 2000).In incorporating the moduli ratio λ/μ into Gray approximation, one can derive this parameter directly.

Assuming $K = \left(\frac{\beta}{\alpha}\right)^2$ is a constant, and $Q = \frac{\lambda}{\mu}$,

$$\frac{\Delta Q}{Q} = \frac{\Delta \lambda}{\lambda} - \frac{\Delta \mu}{\mu}$$

Gray's approximation is reformulated as:

$$R_{PP}(\theta) = \left[\frac{\sec^2\theta}{4} - 2K\sin^2\theta\right]\frac{\Delta\lambda}{\lambda} + \left(\frac{\beta}{\alpha}\right)^2\left[2K\sin^2\theta - \frac{1}{2}K\sec^2\theta\right]\frac{\Delta Q}{Q} + \frac{1}{4}\left[1 - \tan^2\theta\right]\frac{\Delta\rho}{\rho} \quad (2)$$

The amplitudes computed using equation (2) overlies the results of existing AVO approximations.

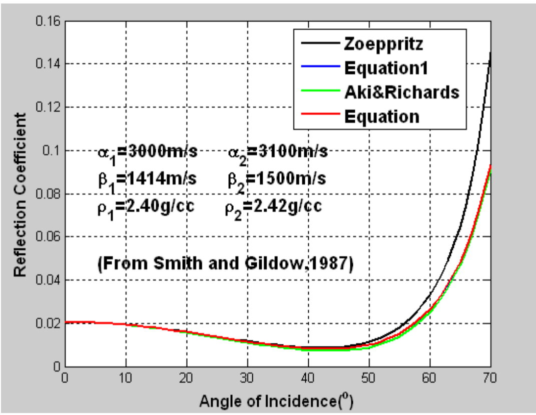

Figure1. A comparison of angle reflection coefficients, $R_{PP}(\theta)$ obtained from equation (2) to those obtained from equation (1), exact Zoeppritz equations and Aki & Richard AVO approximation.

2.2 Elastic impedance

The reflection coefficient $R_{PP}(\theta)$ can be expressed in the same form as the normal incidence AI as:

$$R_{PP}(\theta) = \frac{EI_{i+1} - EI_i}{EI_{i+1} + EI_i} \approx \frac{1}{2}\ln\frac{EI_{i+1}}{EI_i} \quad (3)$$

Where EI_{i+1} is elastic impedance of the lower layer and EI_i is elastic impedance of the upper layer.

Using the same guidelines of previous work (Connolly, 1999) in deriving the EI equation, one can derive the new elastic impedance as:

$$EI_{new}(\theta) = \lambda^{\frac{\sec^2\theta}{2} - 4K\sin^2\theta} Q^{4K\sin^2\theta - K\sec^2\theta} \rho^{1 - \frac{1}{2}\sec^2\theta} \quad (4)$$

To control the variation of elastic impedance values versus angles, one can incorporate normalization parameters which are the average values along the entire log. This reference values can reduce the dimensionality of the equation (4).

$$EI_{new}(\theta) = A_0\left[\frac{\lambda}{\lambda_0}\right]^a\left[\frac{Q}{Q_0}\right]^b\left[\frac{\rho}{\rho_0}\right]^c$$

With $A_0 = \left[8\lambda_0\mu_0\rho_0^2\right]^{0.25}$, $a = \frac{\sec^2\theta}{2} - 4K\sin^2\theta$

$b = 4K\sin^2\theta - K\sec^2\theta$, $c = 1 - \frac{1}{2}\sec^2\theta$

where A_0, λ_0, μ_0 and ρ_0 are references values of P-impedance, Lamé constant, shear modulus and the density ,respectively. It can be shown when the angle of incidence equals zero that EI (0) from equation (5) is equal to acoustic impedance.

2.3 Elastic Impedance Inversion steps

The success of any EI-inversion is largely depended on the quality of seismic traces, the wavelet estimation and the low frequency model which can be estimated in several manners (the most popular being the integration of well logs, interpreted seismic horizons and seismic velocities).

Quality of seismic trace

It well known that removing totally undesirable signal (noise) from seismic data is a thorny question that has been studying so long. To improve signal to noise ratio, offset gathers can be transform into limited angle gather stacks. Three limited angle stack corresponding to near, middle and far angles are created in this paper.

Wavelet estimation

From statistical way (i.e. from seismic data) or from well logging, wavelet must be extracted separately at each limited angle stacks.

Inversion

Post stack inversion methods are used to transform seismic limited angle stack into relative elastic impedances.

Low frequency model

From equation (5), the pseudo elastic impedance logs are computed to constrain the inversion of the seismic limited angle stacks. At well location, seismic limited angle stack and the EI log corresponding to the same incident angle are extrapolated via interpreted horizons to build low frequency model. The latter and the relative elastic impedance are added up to get the absolute elastic impedance section.

2.4 Extraction of Lamé constant, ratio modulus and the density from elastic impedance

In literature, there exist several algorithms aiming to estimate elastic parameters from elastic impedance. Lu et al (2004) have been shown the most common used in which extraction results are largely affected by the K values. To avoid this dependency, lamé parameters can be extracted as follows: from well logging, considering one angle of incidence and three sampling times (t1, t2, t3), the coefficients in the above equation are computed. The same procedure is used to the second and third incidence angles.

$$\ln\{EI_{new}(\theta,t_1)/A_0\} = a\ln\frac{\lambda}{\lambda_0}(t_1) + b\ln\frac{Q}{Q_0}(t_1) + c\ln\frac{\rho}{\rho_0}(t_1) \quad (6)$$

Once the coefficients (9 in total) are obtained, using the linear system with 3 equations (each equation corresponding to an incidence angle), it easy to extract Lamé constant, ratio modulus and the density.

3.0 Well log data synthetic results

To evaluate the effectiveness of the method, one creates synthetic EI data for three angles using equation (5).The lamé parameters logs are computed using P-wave and S-wave velocities. Under free noise, lamé constant λ and the ratio moduli λ/μ (both inverted from equation (5) and indirectly from elastic impedance based on gray approximation) can be successfully recovered (figure 2).

The method is also tested with synthetic noise data. Considering the same data as previously and adding 7% random noise to the seismic reflection, recursive inversion is performed on this data. It's clear in the figures below, that the inversion of λ log from equation (5) is better than from elastic impedance based on gray approximation. From equation (5), the inversion errors related to λ/μ log are not more pronounced than those derived from the inversion based on Gray-approximation .

4. Application to real data

The real data is from a demo dataset distributed with the Hampson-Russell (H-R) inversion package. The 2 D prestack seismic data is inverted to give lamé constant λ, the ratio moduli (λ/μ and the density. When comparing figure (4) and figure (5), it is clear that the new method highlights more better the presence of gas than the method based on gray approximation.

Based on rock physics, incompressibility is the resistance to a change in volume caused by a change in pressure, and can distinguish lithology effects to fluid effects. While rigidity is the resistance to shear stress, thus it is the lithology indicator. The ratio of the two lamé parameters, named lamé moduli ratio λ/μ, shows a low value at 640 ms, indicating the presence of gas.

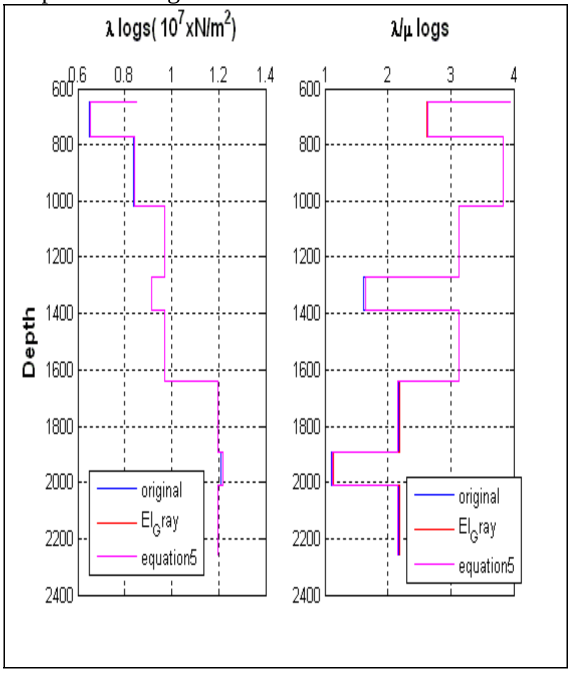

Figure2. Elastic parameters inverted from synthetic EI (equation 5 and elastic impedance based on gray approximation). Left: Lamé constant curves, Right: ratio moduli λ/μ curves. The original log is in blue, λ and λ/μ logs from equation (5) are in magenta, and λ and λ/μ logs from elastic impedance based on gray approximation are in red.

5. Conclusion

In order to derive the lamé ratio moduli, λ/μ directly, the approximation of gray is modified including this parameter. The new approximation in terms of constant lamé, lamé ratio moduli, and density is tested on synthetic and real data. The Synthetic elastic impedance data generated using synthetic well log show that the inversion errors related to λ/μ log are not more pronounced than those derived from the inversion based on Gray-approximation. In addition, the inversion results of real prestack seismic data from a demo dataset distributed with the Hampson-Russell (H-R) inversion packages show that the new method can highlights better the presence of gas than the method based on gray approximation.

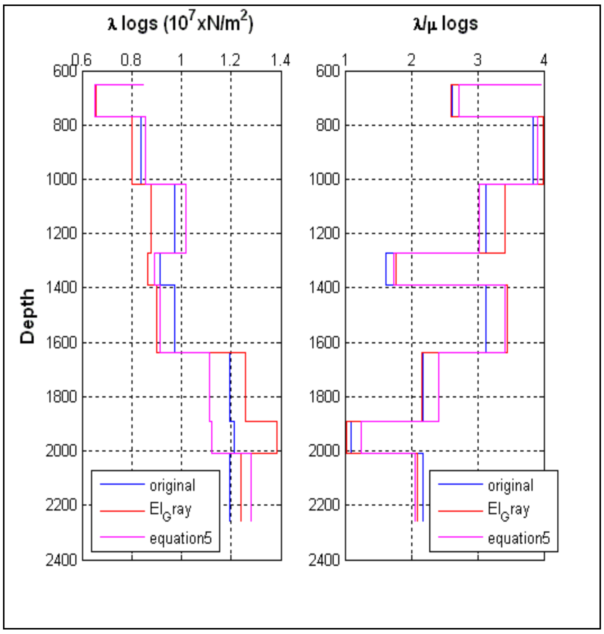

Figure 3: Elastic parameters inverted from synthetic EI (equation 5 and elastic impedance based on gray approximation) using noisy data. Left: Lamé constant curves, Right: ratio moduli λ/μ curves.The original log is in blue, λ and λ/μ logs from equation (5) are in magenta, and λ and λ/μ logs from elastic impedance based on gray approximation are in red.

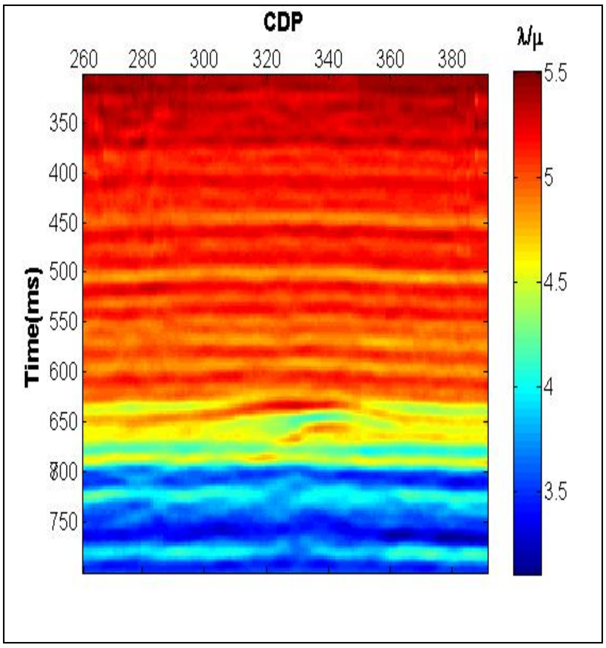

Figure4. λ/μ Profile obtained from elastic impedance based on gray approximation.

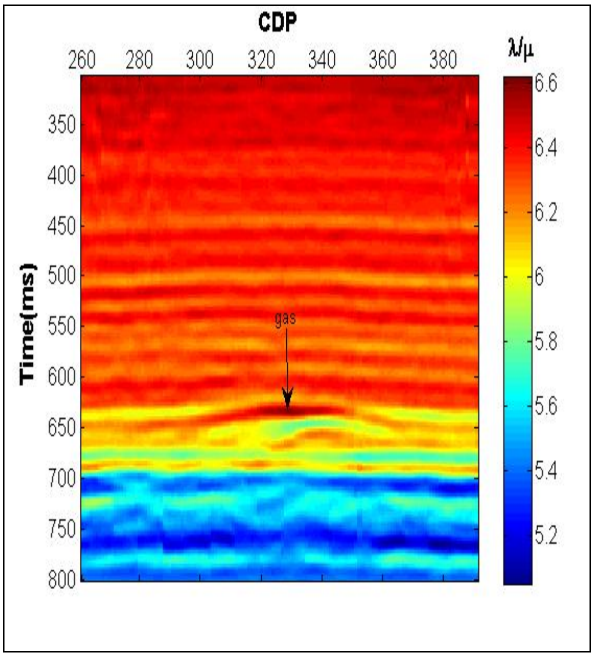

Figure5. λ/μ Profile obtained from the new method.

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