Introduction

Fluid discrimination with seismic data helps to predict the distribution of the oil/gas reservoirs by analyzing the changes of seismic wave velocity, amplitude, frequency and waveform et al. In recent years, people have proposed a variety of fluid anomaly recognition methods based on seismic data (Ren et al., 2009, Ahmed, 2012). It is a current research trend to incorporating the reflection coefficient equation with frequency information and petrophysical theory to make more use of amplitude and frequency information.

Fluid factor is a property that characterizes the reservoir fluid characteristics constructed under the guidance of petrophysics theory. The earliest fluid factor was proposed by Smith and Gidlow (1987), and can be estimated by seismic inversion. Zong et al. (2012) combined the theory of pore elasticity to express the fluid term as a function of the P-wave and S-wave modulus, thereby no need for density information from prestack seismic data. However, these existing fluid factors above are basically conventional fluid factors only considered in terms of elasticity, and the influence on frequency is ignored.

Frequency-dependent AVO inversion is a popular method for predicting frequency-dependent parameters. However, the current approximate equations used for frequency-dependent AVO inversion do not consider viscoelasticity or velocity dispersion characteristics in the medium (Wilson et al., 2009, Zhang et al., 2011, Li et al., 2016). Therefore, it is urgent to combine rock physics theory with reflectivity equation to establish a new reflection coefficient equation well relevant to frequency. In this study, a frequency-dependent viscoelastic solid-liquid decoupling fluid factor is initially established. And then, a new reflection coefficient equation is established which takes into account the effect of viscosity. Finally, the frequency-dependent AVO inversion method was used to estimate the fluid factor. According to the synthetic and field data examples, it is proved that the proposed fluid factor and its predicting approach help to guide fluid identification well.

Method and/or Theory

On the basis of Biot-Gassmann theory, the solid-liquid coupling effects of pore fluids and solid effects of rock skeletons are analyzed through statistical analysis of petrophysics, and the relationship between fluid factor and fluid modulus $K_f$ (Han and Batzle, 2004) is,

$$f = \frac{\beta^2}{\phi} K_f$$  \hspace{1cm} (1)

where, $f$ is the fluid/pore term, $\beta$ is the Biot coefficient, $\phi$ is the effective porosity of the rock.

In order to consider the viscoelasticity of the medium, we use the Futterman approximation constant Q model. And the P wave complex velocity and the S wave complex velocity in the inelastic medium are,

$$\frac{1}{\alpha} = \frac{1}{V_p} \left( 1 - \frac{1}{\pi Q_p} \log \left( \frac{\omega}{\omega_r} \right) + \frac{i}{\pi Q_p} \right)$$

$$\frac{1}{\beta} = \frac{1}{V_s} \left( 1 - \frac{1}{\pi Q_s} \log \left( \frac{\omega}{\omega_r} \right) + \frac{i}{\pi Q_s} \right)$$  \hspace{1cm} (2)

where, $V_p$ and $V_s$ are the P-wave phase velocity and S-wave phase velocity corresponding to the reference frequency $\omega_r$, respectively. $Q_p$ and $Q_s$ are the quality factors of P-wave and S-wave, respectively.

Thus, the fluid factor of inelastic medium can be expressed as,

$$f_{me} = \rho \alpha^2 - \gamma_{\alpha\nu} \rho \beta^2$$

$$= \rho V_p^2 \left( 1 + \frac{2}{\pi Q_p} \log \left( \frac{\omega}{\omega_r} \right) - \frac{i}{Q_p} \right) - \gamma_{\alpha\nu} \rho V_s^2 \left( 1 + \frac{2}{\pi Q_s} \log \left( \frac{\omega}{\omega_r} \right) - \frac{i}{Q_s} \right)$$

$$= f_{me} + \Delta f_q$$  \hspace{1cm} (3)

Similarly, we can obtain the $K_f$ of the inelastic medium,
\[ K_{f,aw} = \frac{\phi}{\beta^2} f_{aw} = \frac{\phi}{\beta^2} (\rho \alpha^2 - \gamma_{dry}^2 \rho \beta^2) \]
\[ = \frac{\phi}{\beta^2} \left[ \rho V_p^2 \left( 1 + \frac{2}{\pi Q_p} \log \left( \frac{\omega}{\omega_r} \right) - i \frac{i}{Q_p} \right) - \gamma_{dry}^2 \rho V_s^2 \left( 1 + \frac{2}{\pi Q_s} \log \left( \frac{\omega}{\omega_r} \right) - i \frac{i}{Q_s} \right) \right] \]
\[ = K_{f,aw} + \Delta K_{f,0} \]

where \( K_{f,aw} \) corresponds to the equivalent fluid bulk modulus in the case of elasticity, and a new disturbance is added in the case of viscoelasticity, namely \( \Delta K_{f,0} \).

Equation (4) is the frequency-dependent solid-liquid decoupling fluid factor we define from the viscoelasticity theory.

The Aki-Richard approximation in the case of viscoelastic media is:
\[ R_{pp}^{aw} (\theta, \omega) = \frac{1}{2} \left( 1 - \frac{4 \sin^2 \theta}{\gamma_{sat}^2} \right) \Delta \rho + \frac{\sec^2 \theta}{2} \frac{\Delta \alpha}{\alpha} - \frac{4 \sin^2 \theta}{\gamma_{sat}^2} \frac{\Delta \beta}{\beta} \]

Based on the above formula, combined with rock physics theory, considering frequency and viscoelasticity, after derivation, a solid-liquid decoupling fluid factor reflection characteristic equation in the case of viscoelastic medium is obtained, as shown below,
\[ R_{pp}^{aw} (\theta, \omega) = \left[ 1 - \frac{\gamma_{dry}^2}{\gamma_{sat}^2} \left( 1 - \frac{2}{\pi Q_p} \log \left( \frac{\omega}{\omega_r} \right) \right) \right] \frac{\sec^2 \theta}{4} \Delta K_{f,aw} \]
\[ + \left( \frac{\gamma_{dry}^2}{4 \gamma_{sat}^2} \sec^2 \theta \frac{2}{\gamma_{sat}^2} \sin^2 \theta \right) \left( 1 - \frac{2}{\pi Q_p} \log \left( \frac{\omega}{\omega_r} \right) \right) \frac{\Delta \mu_m}{\mu_m} \]
\[ + \left[ \frac{\sec^2 \theta}{4} - \frac{2}{\gamma_{sat}^2} \left( 1 - \frac{2}{\pi Q_p} \log \left( \frac{\omega}{\omega_r} \right) \right) \sin^2 \theta \right] \frac{\Delta (\beta^2 \phi^4)}{\beta^2 \phi^4} + \left[ 1 - \frac{\sec^2 \theta}{4} \right] \frac{\Delta \rho}{\rho} \]

where, \( \mu_m = \frac{\phi}{\beta^2} \mu \), \( \gamma_{sat} \) is the ratio of P-wave velocity and S-wave velocity in dry rock, \( \gamma_{dry} \) is the ratio of S-wave velocity and P-wave velocity in fluid-saturated rock, \( \mu_m \) and \( \beta^2 \phi^4 \) are built-up terms without specific physical meaning, which lead to the simplification of the proposed reflectivity equation, and they are addressed as the shear modulus of the rock matrix and porosity divided by the square of Biot coefficient, respectively.

Simplify Equation (6), and perform Taylor expansion and use the amplitude difference information to eliminate frequency-independent terms to obtain the following formula,
\[ \Delta R_{pp}^{aw} (\theta, \omega) = a(\theta) I_{k,aw} \Delta \omega + b(\theta) I_{\mu,a} \Delta \omega \]

where \( \Delta R_{pp}^{aw} (\theta, \omega) = R_{pp}^{aw} (\theta, \omega) - R_{pp}^{aw} (\theta, \omega_0) \),
\[ a(\theta) = \left( 1 - \frac{\gamma_{dry}^2}{\gamma_{sat}^2} \left( 1 - \frac{2}{\pi Q_p} \log \left( \frac{\omega}{\omega_r} \right) \right) \right) \frac{\sec^2 \theta}{4} \],
\[ b(\theta) = \left( \frac{\gamma_{dry}^2}{4 \gamma_{sat}^2} \sec^2 \theta \frac{2}{\gamma_{sat}^2} \sin^2 \theta \right) \left( 1 - \frac{2}{\pi Q_p} \log \left( \frac{\omega}{\omega_r} \right) \right) \frac{\Delta \mu_m}{\mu_m} \]
\[ \Delta \omega = \omega - \omega_0 \], where \( \omega_0 \) is reference frequency. Among them, \( I_{k,aw} \) and \( I_{\mu,a} \) are the frequency-dependent characteristics to be inverted, and they can be used as fluid factors for fluid identification.

Combined with the frequency-dependent AVO inversion method, in the Bayesian framework, \( I_{k,aw} \) and \( I_{\mu,a} \) are obtained to predict the oil/gas properties of the reservoir.

**Examples (Optional)**
In order to verify the feasibility of the frequency-variable solid-liquid decoupling fluid factor AVO inversion method, we first use the logs of a well as a model parameter for data testing. The original $K_{f_{inv}}$ and $\mu_m$ of a well are displayed in blue in Figure 1(a). The pre-stack seismic data is obtained by using the convolution of the exact reflection coefficient equation and the seismic wavelet (Lake wavelet). Then we use the inversion method proposed in this paper to invert the synthesized prestack seismic data. In Figure 1(a), the inversion $K_{f_{inv}}$ and $\mu_m$ of a well are shown in red and the initial model is shown in green, respectively. As can be seen from the figure, the relative prediction errors of these parameters are small. Then, we add random Gaussian noise to the synthetic seismic trace with the S/N is 1:1, 1:2, 2:1, 5:1 and 10:1, respectively. The description and definition of the figures are the same as in Figure 1(a). It can be seen that in the case of noise, we can still get better inversion results of these parameters, and the relative prediction errors are still small.

In order to further test the reliability of the proposed inversion method, the feasibility study of this method is carried out by actual pre-stack seismic angle gather in a work area in eastern China. Figure 2 shows the pre-stack angled partial superimposed seismic data profile extracted from the work area. In this paper, $\omega_r=25Hz$ is selected as the optimal reference frequency, and the frequency division of seismic data is realized by CWT. The frequency-dependent solid-liquid decoupling fluid factor profile obtained by this method is shown in Figure 3. The red block indicating position in the figure is the reservoir development position. From the logging data and the inversion results, the frequency-dependent solid-liquid decoupling fluid factor shows a low value of abnormal energy in the reservoir development position, and the frequency-dependent solid-liquid decoupling fluid factor maintains a high consistency with the logging results.

![Figure 1 Model parameter estimations for $K_{f_{inv}}$ and $\mu_m$ (red means inversion result, blue means original model, green means initial model). (a). without noise; (b). S/N=10; (c). S/N=5; (d). S/N=2.](image)

![Figure 2 Partially superimposed seismic data profiles. (a). near angle superimposed seismic data profile; (b). mid angle superimposed seismic data profile; (c). far angle superimposed seismic data profile.](image)
In this paper, a prestack seismic inversion method for frequency-dependent solid-liquid decoupling fluid factor is proposed to study the underground lithology and oil/gas distribution law. Considering the viscoelasticity of the medium, we construct a solid-liquid decoupling frequency change indicator and derive the reflection characteristic equation. At the same time, the seismic data is frequency-divided to provide a data foundation for the inversion method. Under the framework of Bayesian theory, solving the maximum posterior probability solution, and realizing the extraction of indicator factors finally. This method is in good agreement with the logging curve in practical data applications and has certain practical value.

Compared with the conventional fluid factor inversion method, the method deeply excavates the frequency information contained in the actual data, and realizes the simultaneous measurement of the amplitude and frequency of the seismic record based on the seismic spectrum decomposition, so that the inversion is more stable and accurate. And the method realizes frequency-dependent solid-liquid decoupling fluid factor parameter extraction to reduce oil and gas exploration risk and to realize underground reservoir oil and gas prediction.

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References


