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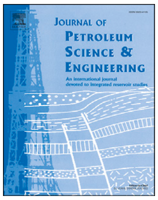

Pre-stack Bayesian cascade AVA inversion in complex-Laplace domain and its application to the broadband data acquired at East China

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ABSTRACT

AVA (amplitude variation with angle) inversion plays an important role in the extraction of lithology and pore fluid information of underground media. To make full use of the limited seismic data and recover much richer low-frequency background of elastic parameters, Bayesian inversion framework, linear model regularization and Laplace mixed-domain forward solver are jointed together to put forward the complex-Laplace mixed domain AVA cascade inversion in this paper. Firstly, the Laplace mixed-domain convolution model is deduced and the magnification phenomenon of low frequency corresponding to seismic data in Laplace mixed domain is analyzed detailedly. Besides, the explicit formulations of pre-stack AVA inversion are constructed based on Laplace mixed-domain operator and Aki-Richard AVA approximation. Then, the objective function in Laplace mixed domain based on Bayesian framework is deduced with the linear initial models of P-wave velocity, S-wave velocity and density. It is worth noting that the proposed algorithm can be separated into two stages: (1) the recovery of much richer low-frequency information with complex-Laplace domain AVA inversion and (2) the estimation of final elastic parameters with pure frequency domain AVA inversion approach. The second stage of cascade AVA inversion is restricted with the low-frequency estimation results in the first stage, which can improve the convergence accuracy of the elastic parameters estimation. Finally, the feasibility of the proposed AVA inversion and the reliability of the fluid discrimination are verified by numerous model tests and one field broadband application in China.

1. Introduction

AVA/AVO (amplitude variation with angle/offset) inversion is an effective technique to predict elastic parameters of underground layers from the analysis of prestack seismic amplitude based on exact or Zoeppritz approximation equation, which plays a significant role in the evaluation of high quality reservoir and the detection of pore fluid information (Russell et al., 2011; Zong et al., 2012). Recent years, the researches on AVA/AVO inversion mainly focus on the optimization of inversion algorithm (Buland and Omre, 2003; Misra and Sacchi, 2008; Alemie and Sacchi, 2011; Zhang et al., 2013; Yin et al., 2016), the stability of multi-parameter prediction (Downton and Ursenbach, 2006; Chen and Yin, 2007; Yang, 2008; Zong et al., 2013; Zhi et al., 2016), the vertical resolution of elastic parameters (Rubino and Velis, 2009; Nguyen and Castagna, 2010; Azevedo et al., 2013; Pérez et al., 2013; Liu et al., 2014; Yin et al., 2015a) and the model parameterization of underground media (Russell et al., 2011; Zong et al., 2012, 2015; Yin and Zhang, 2014). The algorithm optimizations are mainly established to overcome the ill-conditioned problems of AVA inversion, improve the computational efficiency and enhance the reliability of estimated parameters. Considering the stability of the multi-parameter prediction, numerous studies of AVA inversion based on the exact or high-order Zoeppritz equation and the decorrelation of multi-parameter were developed (Zhu and McMechan, 2012; Zong et al., 2013; Lu et al., 2015; Zhi et al., 2016). The resolution of AVA inversion has been an eternal topic for many years and the main improved approaches include spectral inversion, stochastic inversion and geostatistics inversion (Portniaguine and Castagna, 2005; Rubino and Velis, 2009; Azevedo et al., 2013). Model parameterized AVA inversion mainly involves the quantitative characterization of petrophysical property (Doyen, 1988; Buland et al., 2008; Yin et al., 2014), the prediction of pore fluid types, the evaluation of rock brittleness and ‘sweet spots’ in conventional and unconventional reservoirs (Yin et al., 2015b; Zong and

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Yin, 2016). According to the difference of transform domain in which the objective function is established, the AVA seismic inversion can mainly be divided into time-domain inversion, frequency-domain inversion, time-frequency domain inversion and other inversion methods.

Since the time-domain inversion is more intuitive and has better anti-noise ability, time-domain AVA inversion is developing more rapidly compared with AVA inversion in other domains (Yin et al., 2016). Assuming the sparse characteristics of time domain reflectivity, the sparse AVA inversion based on parity decomposition of reflectivity can restore the block elastic parameters and yields broadband inversion results. Briefly speaking, any regularization means in AVO/AVA inversion are introduced to achieve the purpose of suppressing the background noise and restricting the model space by balancing the weights between synthetic data and regularization terms (Alemie and Sacchi, 2011; Downton, 2005; Tarantola, 2005; Buland and Omre, 2003; Theune et al., 2010). According to different types of sparse regularization in time domain, there are mainly four constraints including L_0-norm AVA inversion (matching pursuit algorithm), L_1-norm AVA inversion (basis pursuit), L_p mixed-norm ($0 < p < 1$) AVA inversion and other sparse prior models expressed by probability density function (PDF) in probabilistic approaches (Nguyen and Castagna, 2010; Zhang et al., 2013; Liu et al., 2014; Yin et al., 2015a). Geophysicists also introduced the bounding constraints, low-frequency constraints and priori geological constraints to time-domain seismic inversion to compensate for the lack of long-wavelength components of the elastic parameters. By using these low-frequency constraints in seismic inversion, the reliability and stability of seismic inversion can be improved effectively (Gelderblom and Leguijt, 2010; Kroode et al., 2013; Zong and Yin, 2016; Li et al., 2016a). Different with the time-domain AVA inversion, the seismic data can be decoupled automatically in frequency domain and the inverse problem with different frequencies can be solved independently. There are two major inversion strategies corresponding to frequency-domain seismic inversion: spectral inversion and mixed-domain inversion.

The objective function of spectral inversion is established in short-time Fourier domain combined with odd-even decomposition of the reflectivity. By adjusting the window length and the position of time center, spectral inversion can achieve high resolution inversion results and is applied to distinguish the thin-beds within tuning thickness (Portniaguine and Castagna, 2005; Chopra et al., 2006; Puryear and Castagna, 2008; Rubino and Velis, 2009). The mixed-domain AVA inversion is mainly implemented based on the Robinson mixed domain convolution to avoid the cumulative errors of the inverse Fourier transform, which combines the time-domain reflectivity of elastic parameters, frequency-domain seismic response and wavelet spectrum (Yuan and Wang, 2009, 2013; Chai et al., 2015; Wang et al., 2014; Li et al., 2015, 2016b). The attenuation and dispersion effects resulting from the inhomogeneity and viscosity of underground media can be introduced easily in time-frequency domain inversion. The major time-frequency domain inversion approaches include Gabor deconvolution of nonstationary data (Margrave, 1998; Margrave et al., 2011), inverse spectral decomposition (Portniaguine and Castagna, 2004; Han et al., 2011) and frequency-dependent AVA inversion (Wilson et al., 2009; Wu et al., 2010; Li et al., 2016c).

A reliable low frequency background of elastic parameter is the prerequisite for obtaining the absolute elastic parameters of the reservoir (Shin and Cha, 2009; Kroode et al., 2013; Zong and Yin, 2016; Li et al., 2016a). Besides, most of AVA inversion approaches are based on model constraints and the reliability of inversion results is seriously dependent on the accuracy of the initial model at present. To decrease the model-dependent problem in seismic inversion, the seismic inversion in pure frequency domain was modified into complex Laplace-Fourier domain inversion when the damping effect was appended in the pure frequency domain (Sirgue and Pratt, 2004; Brenders and Pratt, 2007; Shin and Cha, 2008, 2009). And seismic inversion performed in Laplace-Fourier domain helps to recover long-wavelength background of the elastic parameters (Shin and Cha, 2008, 2009). Based on the previous research results, one novel pre-stack AVA inversion approach in complex Laplace mixed domain is proposed with Bayesian estimation framework in this paper. And the forward operator of proposed method is the Laplace mixed domain convolution model (Li et al., 2016b). Firstly, much richer low frequency background of elastic parameters can be retrieved with the proposed complex Laplace domain AVA inversion. In this process, the linear initial model, the Laplace spectrum (less than 5 Hz) and the appropriate damping coefficients σ are utilized for the input of the proposed approach. And then, with the constraints of low-frequency estimation results, absolute elastic parameters can be predicted by multi-frequency stepwise iterations algorithm in pure frequency domain. In addition, the influences of different frequency components and attenuation coefficients on complex Laplace domain AVA inversion are uncovered by numerous synthetic examples. Finally, the feasibility of the proposed inversion algorithm is also demonstrated by one field broadband application from east of China.

2. Bayesian cascade AVA inversion in complex-Laplace domain

2.1. Complex-Laplace domain forward operator

The Laplace transformation of an time-domain seismic trace $y(t)$ can be defined as the Fourier transforms of several attenuated signals $y(t)\cdot e^{-\sigma t}$, and can be expressed in complex frequency domain,

$$Y(s) = \int_{-\infty}^{+\infty} \hat{y}(t) e^{-i2\pi f t} dt = \int_{-\infty}^{+\infty} y(t) e^{-\sigma t} e^{-i2\pi f t} dt \tag{1}$$

where $\hat{y}(t)$ indicates the attenuated response, $y(t)$ represents the original signal, f is the frequency, σ is the damping coefficient, s is complex frequency $\sigma + i2\pi f$, $Y(s)$ is the Laplace spectrum of $y(t)$. To establish the complex-Laplace domain equation of stationary convolution, we can substitute Robinson model (Robinson, 1957; Robinson and Treitel, 1967) for $y(t)$ in equation (1) and the Laplace mixed domain forward operator can be written as

$$Y(\sigma + i2\pi f) = W(\sigma + i2\pi f) \int_{-\infty}^{+\infty} m(\tau) \cdot e^{-\sigma\tau} e^{-i2\pi f \tau} d\tau \tag{2}$$

where $W(\sigma + i2\pi f)$ represents the Laplace spectrum of wavelet, $m(\tau)$ is the underground reflectivity, $e^{-\sigma\tau}\cdot e^{-i2\pi f\tau}$ refers to the time attenuation and Laplace operator. The forward equation (2) indicates the simple knowledge that Laplace spectrum of field seismic wave can be expressed as the product of the Laplace spectrum of wavelet and reflectivity. So, if the Laplace spectrums of seismic wave and wavelet can be collected, the underground reflectivity $m(\tau)$ can be predicted easily by effective inversion algorithms. Unfortunately, the collection of sufficient amount of field data is always difficult for geophysicists and the band-limited characteristic of seismic data will lead to the ill-posedness of our prediction works (Tarantola, 2005; Buland and Omre, 2003; Downton and Ursenbach, 2006; Chen and Yin, 2007; Yin et al., 2016). For these reasons, geophysicists have strived to develop many effective approaches for the reduction of multiple-solutions, evaluation of inverse uncertainty, improvement of inverse stability and enhancement of inverse resolution in pre-stack seismic AVA inversion (Ulrych et al., 2001; Tarantola, 2005; Nguyen and Castagna, 2010; Theune et al., 2010; Yin et al., 2014). Prior information and regularization constraints are two popular strategies to deal with the ill-posed problem. However, the model-dependent problem still exists in AVA inversion and the accuracy of initial model representing the low frequency components affects the prediction reliability of elastic parameters seriously (Shin and Cha, 2009; Kroode et al., 2013; Zong and Yin, 2016; Li et al., 2016b). In this study, the Laplace mixed-domain model of seismic reflection is regarded as the forward operator in cascade AVA inversion which is helpful to restore the long-wavelength information of underground structure.

To illustrate the importance of Laplace mixed-domain model to low-frequency restoration, a series of synthetic attenuated data, attenuated wavelets and Laplace spectrums of theoretical signals are displayed in Figs. 1–3. Fig. 1 shows several damped 30 Hz wavelets and synthetic