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Nonlinear inversion of pre-stack seismic data using variable metric method

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ABSTRACT

At present, the routine method to perform AVA (Amplitude Variation with incident Angle) inversion is based on the assumption that the ratio of S-wave velocity to P-wave velocity γ is a constant. However, this simplified assumption does not always hold, and it is necessary to use nonlinear inversion method to solve it. Based on Bayesian theory, the objective function for nonlinear AVA inversion is established and γ is considered as an unknown model parameter. Then, variable metric method with a strategy of periodically variational starting point is used to solve the nonlinear AVA inverse problem. The proposed method can keep the inverted reservoir parameters approach to the actual solution and has been performed on both synthetic and real data. The inversion results suggest that the proposed method can solve the nonlinear inverse problem and get accurate solutions even without the knowledge of γ.

1. Introduction

The ultimate aim of AVA or AVO inversion is to obtain the earth's elastic parameters, such as P-wave velocity, S-wave velocity, Poisson's ratio and density from pre-stack seismic gathers. Its theoretical foundation is Zoeppritz equations (Zoeppritz, 1919). However, the Zoeppritz equations are too complicated to practical applications. Many scholars have derived different approximations and started from different aspects of the problem (Ostrander, 1984; Shuey, 1985; Smith and Gidlow, 1987; Fatti et al., 1994; Verm and Hilterman, 1995; Gray et al., 1999; Wang, 1999a, b; Aki and Richards, 2002; Gui et al., 2011; Russell et al., 2011; Zong et al., 2012, 2013). Based on these approximations of P-wave reflection coefficient, the routine methods to perform pre-stack seismic inversion are the simultaneous inversion (Hampson et al., 2005) and the elastic impedance inversion (Connolly, 1999; Wang et al., 2006). Both methods consider the ratio of S-wave velocity to P-wave velocityγ as a constant. Under this assumption, the nonlinear inverse problem becomes linear, and stable results can be obtained by the least square strategy. However, when the assumption is no longer satisfied (Wang, 2003a), nonlinear inversion strategy becomes inevitable.

Nonlinear inversion algorithms have been introduced to perform AVA inversion for many years. Hu et al. (2000) proposed a generalized linear inversion method by combining the nonlinear optimization theory with geophysical inverse problems, and discussed its stability and computational efficiency. When applied in AVA inversion, they derived the analytic equations of gradient vector and Hessian matrix, and pointed out that gradient dependent method is faster than stochastic method, such as simulated annealing (Kirkpatrick et al., 1983; Misra and Sacchi, 2008; Varela et al., 2006), or genetic algorithm (Scales and Smith, 1994). Wang et al. (2000) used Hessian matrix together with a damping matrix, in a multistage damped subspace method to solve the inverse problem. Li and Xu (2002) described the principle of nonlinear AVA inversion as well as the construction of objective function and calculation of Hessian matrix. They obtained accurate Poisson's ratio and directly detected gas reservoirs. Varela et al. (2006) added smoothness constraints into the objective function and used simulated annealing algorithm to solve the nonlinear AVA inverse problem. In order to get more stable inversion results, Misra and Sacchi (2008) used an improved simulated annealing algorithm which is called fast simulated annealing algorithm to solve the nonlinear problem. These inversion methods either need to directly solve computationally intensive and unstable Hessian matrix, or take a long time to run simulated annealing algorithm.

In this paper, based on the Bayesian theory, the objective function for nonlinear AVA inversion is established, in which γ is considered as an unknown parameter. Then, variable metric method (Davidon, 1959, 1991; Fletcher and Powell, 1963; Fletcher, 2000) is used to solve this problem. The advantage of the variable metric method is that it can avoid the direct calculation of Hessian matrix, and ensure to get a stable solution.

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2. Nonlinear AVA inversion

2.1. Forward equation for nonlinear AVA inversion

The approximate equation of P-wave reflection coefficient derived by Aki and Richards (2002) is the base of AVA inversion. In seismic inversion, parameters which have clear physical meaning and good stability are often used (Yang et al., 2009). Many scholars (Debski and Tarantola, 1995; Downton and Lines, 2001) pointed out that P- and S-wave impedance inversion is more stable than velocity inversion. Hence we use Fatti's equation (Fatti et al., 1994) as the forward equation, which is

$$R(\theta) = \sec^2\theta R_p - 8\gamma^2 \sin^2\theta R_s + \left(4\gamma^2 \sin^2\theta - \tan^2\theta\right) R_\rho, \tag{1}$$

where $R(\theta)$ is the reflection coefficient changed with incident angle θ; $R_p = \frac{dI_p}{2I_p}, R_s = \frac{dI_s}{2I_s}, R_\rho = \frac{d\rho}{2\rho}$ are P-wave impedance reflectivity, S-wave impedance reflectivity and density reflectivity, respectively; I_p is P-wave impedance, I_s is S-wave impedance, and ρ is density; $\gamma = \frac{v_s}{v_p}$ in which v_p is P-wave velocity and v_s is S-wave velocity. From Eq. (1) we can see that both γ and R_p, R_s, R_ρ are unknown. It is a nonlinear equation with respect to γ.

Let

$$a(\gamma, \theta) = \sec^2\theta, \tag{2}$$

$$b(\gamma, \theta) = -8\gamma^2 \sin^2\theta, \tag{3}$$

$$c(\gamma, \theta) = \left(4\gamma^2 \sin^2\theta - \tan^2\theta\right), \tag{4}$$

Eq. (1) can be written in matrix form for n incident angles

$$\begin{bmatrix} R(\theta_1) \\ R(\theta_2) \\ \vdots \\ R(\theta_n) \end{bmatrix} = \begin{bmatrix} a(\gamma,\theta_1) & b(\gamma,\theta_1) & c(\gamma,\theta_1) \\ a(\gamma,\theta_2) & b(\gamma,\theta_2) & c(\gamma,\theta_2) \\ \vdots & \vdots & \vdots \\ a(\gamma,\theta_n) & b(\gamma,\theta_n) & c(\gamma,\theta_n) \end{bmatrix} \begin{bmatrix} R_p \\ R_s \\ R_\rho \end{bmatrix}, \tag{5}$$

where, $\theta_1, \theta_2, \cdots \theta_n$ represents n different incident angles.

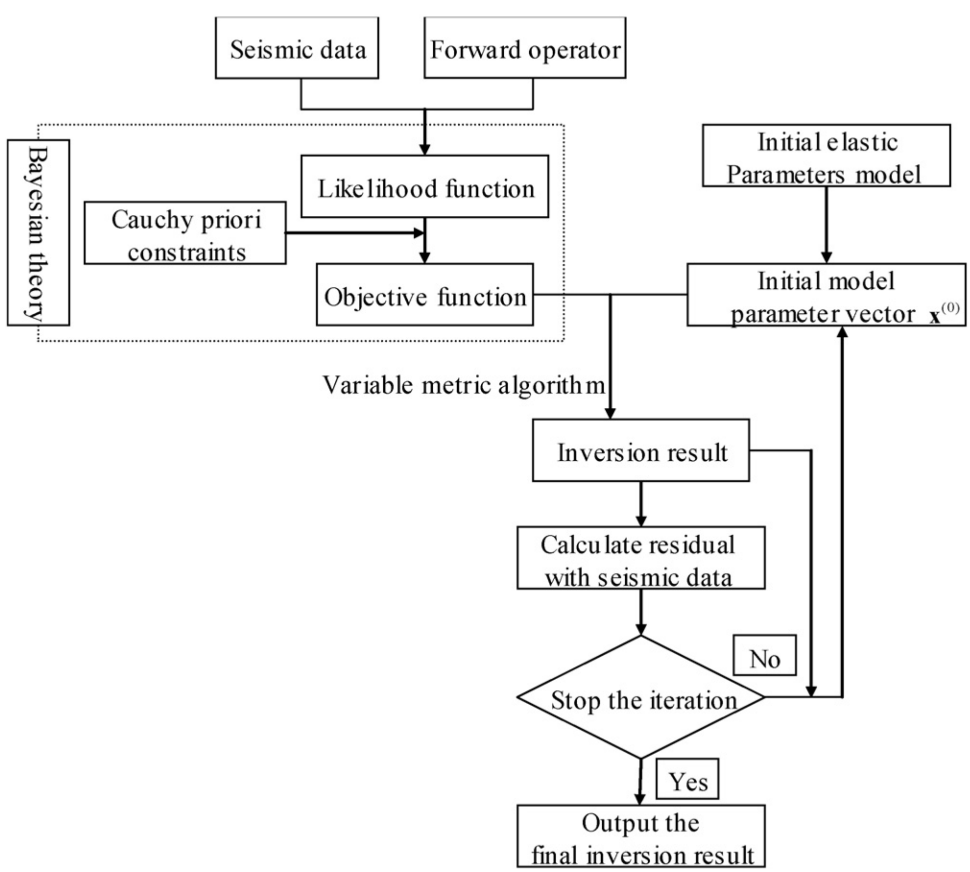

Fig. 1. Flowchart of the proposed inversion method.