APPLICATION NICHE GENETIC ALGORITHMS TO AVOA INVERSION IN ORTHORHOMBIC MEDIA

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A forward modeling of P-wave propagation in a bi-layer model of an isotropic layer overlying an orthorhombic layer is performed. The observation data of four differently oriented common-midpoint (CMP) lines show that P-wave amplitude exhibit strong azimuthal anisotropy. A formula is deduced to obtain the azimuth angle by using the amplitude variation of four differently oriented lines. Thomsen anisotropic parameters and the ratio of SV- wave and P-wave vertical velocity can be inverted from Amplitude Versus Offset and Azimuth (AVOA) by using the Niche Genetic Algorithms (NGA).The numerical simulation shows that the inversion method has enough stabilization and precision.

1. Introduction

Seismic detection of subsurface fracture plays an important role in making decisions on drilling locations and determining fluid flow during production[1-2]. Natural fractures in reservoirs tend to be vertical to the minimum horizontal in-situ stress, so the horizontal transverse isotropy (HTI) model is commonly used to describe a system of parallel vertical penny-shaped cracks embedded in an isotropic host rock. Some scholars have done many researches on fracture prediction by using the properties of azimuthal anisotropy of seismic wave velocities and reflection amplitudes in HTI media, and have obtained some theoretical achievements and oilfield data processing experiences[3-7]. However, the orthorhombic model (ORT) is believed to be more realistic than HTI model to describe the naturally-fractured reservoirs. The approximate reflection coefficient for a bi-layer model of an isotropic layer overlying an orthorhombic layer has been derived by Corrigan[8] in 1990. In terms of the similar form of the symmetry planes of orthorhombic media and transverse isotropy media, Tsvankin[9] introduced Thomsen-style anisotropic parameters[10] of transverse isotropy model into P-wave kinematic study on ORT model to deduce a series of simplified velocity formulae. In the same way, Ruger[1] presented a modified P-wave reflection coefficient formula in ORT media, which is the basis for our study on AVOA inversion. It is known that the inversion algorithm is an important factor to affect the results of inversion. In respect that most of the optimization problems in geophysical prospecting are nonlinear, the conventional Newton's method or gradient method are prone to trapping in local minima. To overcome the problems above, Genetic Algorithm (GA) or simulated annealing algorithm etc. are often applied to nonlinear inversion. As a modified GA, the Niche Genetic Algorithm (NGA) can maintain the population various, meanwhile owns the properties of preventing premature convergence[11]. Therefore, we apply the Niche Genetic Algorithm to the AVOA inversion of fracture parameters in ORT media and obtain a highly precise inversion results.

2. AVOA for ORT Media

The P-wave reflection coefficient for ORT medium has been given by Ruger[1] as

$$R(i,\phi)=\frac{1}{2}\frac{\Delta Z}{\overline{Z}}+\frac{1}{2}\left\{\frac{\Delta\alpha}{\overline{\alpha}}-(\frac{2\overline{\beta}}{\overline{\alpha}})^2\frac{\Delta G}{\overline{G}}+\left[\Delta\delta^{(2)}+2(\frac{2\overline{\beta}}{\overline{\alpha}})^2\Delta\gamma\right]\cos^2\phi+\Delta\delta^{(1)}\sin^2\phi\right\}\sin^2 i, \quad (1)$$

where i denotes the incidence phase angle, Φ is the azimuthal angle defined in this paper as the angle between the $[x_1,x_3]$ symmetry plane and the first survey line oriented eastward (as shown in Fig.1). $Z=\rho\alpha$ is P-wave impedance and $G=\rho\beta^2$ denotes the SV-wave shear modulus. The average velocity $\overline{\alpha}=1/2(\alpha_2+\alpha_1)$ and the difference $\Delta\alpha=\alpha_2-\alpha_1$ can be respectively written as functions of the P-wave vertical velocities α_1 and α_2 in the upper and lower layer. Corresponding expressions are defined for the shear modulus, the density, and the P-wave impedance. This is similar for Thomsen anisotropy parameters $\Delta\varepsilon$, $\Delta\delta^{(1)}$, $\Delta\delta^{(2)}$, and $\Delta\gamma$, among which $\Delta\gamma$ relates to the density of fractures linearly[7].

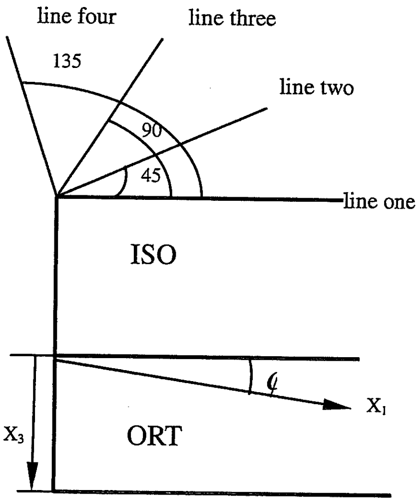

Fig. 1. Orientation of four survey lines for an isotropic layer overlying an ORT medium.

In a 2-D survey, reflection amplitudes are recorded at different offsets and azimuths and strong AVOZ is observed in ORT media (shown in Fig.2). Therefore, it is possible to invert fracture orientation and density from AVOZ information. Generally speaking, the azimuth angle is unknown ahead of inversion. In this paper, we define the first survey line oriented eastward as the baseline, then put the second line at the direction of 45degree east-north, and put the third line oriented northward, finally put the fourth line at the direction of 135degree east-north (shown in Fig.1). When we get the observation data of the four lines, we can deduce the azimuth angle in terms of the amplitudes variations among the four lines.

From equation (1), we can deduce

$$R(i,\phi)-R(i,\phi+90)=\frac{1}{2}\left[\Delta\delta^{(2)}+2(\frac{2\overline{\beta}}{\overline{\alpha}})^2\Delta\gamma-\Delta\delta^{(1)}\right]\cos 2\phi\sin^2 i\,, \quad (2)$$

and

$$R(i,\phi+45)-R(i,\phi+135)=\frac{1}{2}\left[\Delta\delta^{(1)}-\Delta\delta^{(2)}-2(\frac{2\overline{\beta}}{\overline{\alpha}})^2\Delta\gamma\right]\sin 2\phi\sin^2 i\,. \quad (3)$$

According to the equations above, we can obtain the azimuthal angle by

$$\phi=\arctan\left(\frac{R(i,\phi+135)-R(i,\phi+45)}{R(i,\phi)-R(i,\phi+90)}\right), \quad (4)$$

where *R(i,Φ), R(i,Φ+45), R(i,Φ+90), R(i,Φ+135)* are the reflection coefficients for the first, the second, the third and the fourth line.

When the azimuthal angle *Φ* is know, Thomsen anisotropic parameters $\Delta\delta^{(1)}$, $\Delta\delta^{(2)}$, $\Delta\gamma$ and the ratio of SV- wave and P-wave vertical velocity (to simplified as $g=\frac{\overline{\beta}}{\overline{\alpha}}$) can be obtained by performing some nonlinear optimizing inversion according to equation (2) or equation (3).

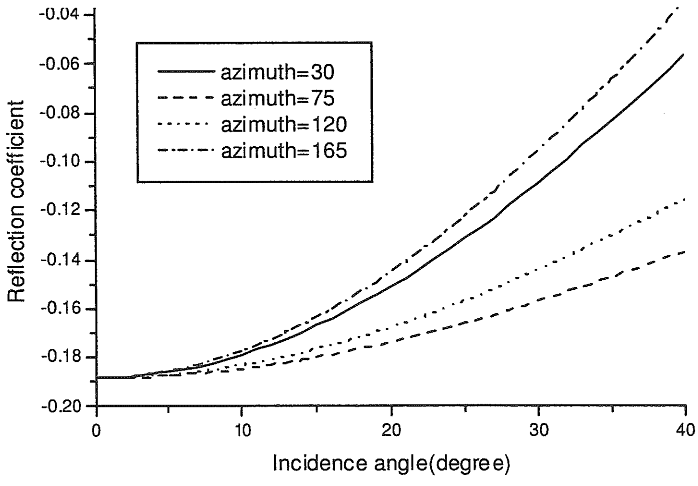

Fig. 2. Reflection coefficient for an isotropic layer overlying an isotropic layer overlying an ORT medium for azimuth of 30(solid),75(dash),120(dot),165(dash dot). Table 1 lists the model parameters.

3. NGA Inversion Algorithm

For complex nonlinear optimization problem, the conventional GA is prone to trapping in local minima owing to its searching the extreme point in a population, which is also named premature convergence. To overcome the problem above, the population variety should be maintained during the evolutionary process. In some other words, the optimum solution and the extreme solution must be co-existed during the search process to ensure the global optimum solution be obtained by comparing some peaks of every population.

The NGA is one of the modified algorithms to overcome the problem above, whose basic idea concludes[11]: the individuals of many populations are relatively independent in propagation for extending the search space, and the population variety is maintained by controlling the fitness of the individual. The NGA in this paper combines the benefits of the distance isolation model and the panmixia model, which are applied to the optimizing inversion of multi-parameters. The basic idea of the distance isolation model is to divide a population into many smaller populations (islands), and make the individuals propagate independently in a small population, and commute individuals among the populations. The idea of the panmixia model is embodied in the improved standard fitness sharing method. The sharing function S_h is defined as

$$S_h(d_{ij}) = \begin{cases} 1 - d_{ij}/\sigma & d_{ij} < \sigma \\ 0 & \text{other} \end{cases}, \tag{5}$$

where σ is the given niche radius, d_{ij} is the distance from the individual i and the individual j. Then the sharing fitness is

$$f'(x_i) = f(x_i) \Big/ \sum_{j=1}^{N} S_h(d_{ij}). \tag{6}$$

In every population, when one individual is close to another one, its sharing fitness will reduce largely to make it easy to be eliminated, whereas its fitness will decrease little. Therefore, the rare individuals can be maintained and propagated and the population variety is preserved very well. This algorithm can prevent premature convergence and hold the properties of global optimum and fast convergence, especially for the complex multi-mode optimization problem.

The essence of inversing Thomsen parameters by NGA is an optimization problem of seeking the adequate model parameters $p(p_1, p_2, \ldots p_n)$ to make the theoretical predicted results match with the observation data. The objective function $E(p)$ is defined as

$$E(p)=\sqrt{\frac{C}{N}\sum_{i=1}^{N}[R_P(p,i)-R_P^*(i)]^2}\quad, \tag{7}$$

where $R_P(p,i)$ is the ith predicted amplitude of P-wave, $R_P^*(i)$ is the ith observation data, C is the amplified number, and N is the number of sample.

4. Numerical Simulation

In order to test the effectivity of our inversion method, we perform a numerical simulation inversion process. First, we substitute the amplitudes calculated in equation (1) for the observation data required before inversion. The numerical simulation model is a bi-layer one of an isotropic layer overlying an ORT media. The elastic tensor of ORT media is as follows (referred to literature 12):

$$C=\begin{bmatrix} 30.779 & 3.163 & 3.551 & 0 & 0 & 0 \\ 3.163 & 23.611 & 2.801 & 0 & 0 & 0 \\ 3.551 & 2.801 & 22.941 & 0 & 0 & 0 \\ 0 & 0 & 0 & 7.903 & 0 & 0 \\ 0 & 0 & 0 & 0 & 9.386 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10.558 \end{bmatrix}.$$

The parameters of velocities and Thomsen parameters in ORT media are calculated according to the equations in reference [3,9], and the results are listed in Table 1 with the parameters of the isotropic layer.

Next, substitute the values of these parameters in Equation (1) and obtain four sets of amplitudes when the azimuthal angle is 30°, 75°, 120°and 165° respectively as observation data of four survey lines.

Table 1. Parameters of the bi-layer model.

parameter value	ρ (kg/m^3)	α (m/s)	β (m/s)	$\delta^{(1)}$	$\delta^{(2)}$	γ	ϕ (°)
ISO media	2600	4000	2200	0	0	0	0
ORT media	2200	3229	1895	-0.16	-0.026	0.168	30

Second, we substitute four sets of amplitudes in Equation (5), and obtain a curve of illustrating the relationship between the azimuthal angle and the incidence angle. Fig.3 shows that the azimuthal angle inverted is approximated as 30°and it is highly accurate compared with the real value.

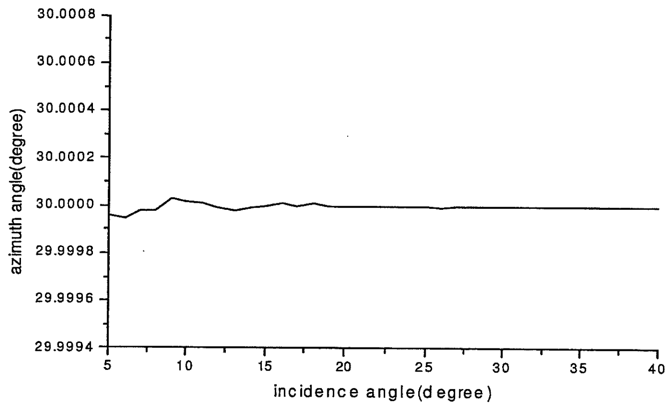

Fig.3. The azimuthal angle inverted.

Third, we use the NGA to invert Thomsen parameters $\Delta\delta$, $\Delta\gamma$ and g from the amplitudes difference between line one and line three.

The parameters of NGA are selected as: the population number is 4, the number of individuals in every population is 50, the crossover probability is $P_c = 0.8$, the mutation probability is $P_m = 0.01$, the ratio of selection from the parent population is 70%, and the generation number is 30. The ranges of inversion parameters are $-0.2 \leq \Delta\delta^{(1)} \leq 0$, $-0.1 \leq \Delta\delta^{(2)} \leq 0$, $0 \leq \Delta\gamma \leq 0.2$, $0.5 \leq g \leq 0.8$ respectively. The objective function is defined as formula (7) and the amplified number C = 1.0E + 6. The inversion results and errors are shown in table 2.

Table 2 Comparison between inversion results and true values.

parameters	$\Delta\delta^{(1)}$	$\Delta\delta^{(2)}$	$\Delta\gamma$	g
real value	-0.16	-0.026	0.168	0.566
inverted value	-0.18	-0.027	0.164	0.558
absolute error	0.02	0.001	0.004	0.008
relative error	12.5%	3.8%	2.3%	1.4%

From table 2, we can conclude that the results of inversion accord well with the real values of model parameters. The ratio of SV- wave and P-wave vertical velocity inverted has the smallest error, which can provide a way to estimate SV- wave vertical velocity accurately because it is difficult to acquire SV- wave vertical velocity directly from the oilfield observation. The relative error of $\Delta\gamma$ parameter is only 2.3%, so it is accurate enough to predict the density of fractures. On Fig.4, we can see that the convergence of the objective function tends to be stable after the 20th generation, which shows that our inversion algorithm has fast and stable convergence.

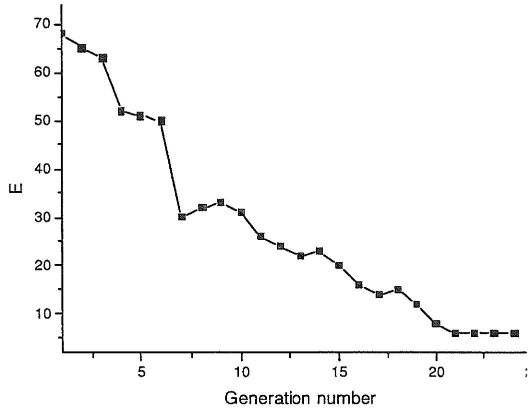

Fig.4 The convergence of objective function

5. Conclusions

In studies of naturally-fractured reservoirs, the orthorhombic model (ORT) is more realistic than horizontal transverse isotropy (HTI) model. In respect that P-wave amplitudes are very sensitive to azimuthal seismic anisotropy, the properties of AVOA can be applied to fracture detection. In this paper, a new method using the amplitudes variation of four differently oriented common-midpoint (CMP) lines to obtain a highly accurate azimuth angle is proposed; the procedure of AVOA inversion of Thomsen anisotropic parameters by using the Niche Genetic Algorithms is described in detail. The numerical simulation shows that the direction and density of fractures inverted are highly accurate and the Niche Genetic Algorithms has enough stabilization and precision. Further study will focus on extending this inversion method to the processing of the oilfield seismic data.

Acknowledgments

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