Efficient Double-Beam Characterization for Fractured Reservoir

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Abstract

We proposed an efficient target-oriented method to characterize seismic properties of fractured reservoirs: the spacing between fractures and the fracture orientation. Based on the diffraction theory, the scattered wave vector is related to the incident wave vector computed from the source to the target using a background velocity model. Two Gaussian beams, a source beam constructed along the incident direction and a receiver beam along the scattered direction, interfere with each other. We then scan all possible fracture spacing and orientation and output an interference pattern as a function of the spacing and orientation the most likely fracture spacing and orientation can be inferred. Our method is adaptive for a variety of seismic acquisition geometries. If seismic sources (or receivers) are sparse spatially, we can shrink the source (or receiver) beam-width to zero and in this case, we achieve point-source-to-beam interference. We validated our algorithm using a synthetic dataset created by a finite difference scheme with the linear-slip boundary condition, which describes the wave-fracture interaction.

Introduction

Naturally fractured reservoirs are documented almost everywhere and most worlds' oil is from fractured reservoirs. Exploring new reservoirs and enhancing the recovery factor for existing reservoirs are the main themes in the current fossil energy landscape. A key element is to obtain an accurate permeability field. Current reservoir simulators have evolved to a state that has already outpaced our ability to supplying a reliable and detailed permeability field. It has been shown that by incorporating a detailed permeability map the predicted well production matches better than using the up-scaled permeability field. For fractured reservoirs, fractures, voids and vugs are ubiquitous features, although small in volume but when interconnected or aligned with each other due to local tectonic stress, they may provide preferable fluid flow paths and therefore they can be more important than the matrix permeability. Reliable assessment of properties of fractures is critical for the oil recovery.

The type of information we are interested in includes fracture orientation, fracture density or spacing and fracture compliance. Widely used seismic methods to characterize fractured reservoirs include shear wave splitting (Vetri *et al.*, 2003) and the amplitude-versus-angle-and-azimuths (AVAz) for P waves (Ruger and Tsvankin, 1997). These methods regard the vertically fractured medium as an equivalent anisotropic medium (HTI) with a horizontal symmetry axis. It is essentially a long-wavelength approximation, which requires that there are many fractures per wavelength. *Tatham et al.* (1992) showed that at least 10 fractures per wavelength is needed for the fractured medium to be viewed as an equivalent anisotropic. However, complex overburden geological structures will make the CDP-based method less accurate and the uneven illumination can also cause bias in the P wave AVAz analysis. So we need a method, which can account for complex wave phenomenon in the overlying structures. The method should also be able to extract spatially varying fracture information as well as account for the uneven seismic illumination. If the fracture spacing is close to the wavelength, one needs scattering theory to characterize the fractures (Willis *et al.*, 2006; Zhang *et al.*, 2006; Burns *et al.*, 2007; Zheng *et al.*, 2011).

Here we develop a double-beam stacking method. The method is a phase-space method and it can provide spatially varying fracture properties for a wide range of scales. Therefore, it is localized in the spatial as well as in the angular domains, necessary for balancing the uneven illumination. Before we go into the inverse problem of finding fracture orientation and spacing, let us take a look on how fractures scatter seismic waves. For simplicity, we consider plane wave scattering by periodic structures. Scattering by non-periodic structures is a straightforward extension by windowing.

Method and Theory

Here we aim at developing such a new scheme, which we call the *double-beam stacking method*. The method is a phase-space method and it can provide spatially varying fracture properties for a wide range of scales. Therefore, it is localized in the spatial as well as in the angular domains (Figure 1), necessary for balancing the uneven illumination. Fracture information within the interference zone (pink area in Figure 1) is extracted. The 5-dimensional seismic data can be represented as $p\left(\mathbf{x}_s,\mathbf{x}_g,t\right)$ where symbols $\mathbf{x_s}$, $\mathbf{x_g}$ and t are source location, receiver location and time, respectively. The double-beam stacking is an *f-k* analysis for the localized data, resulting in a 10-dimensional dataset (Figure 1):

$$B\left(\mathbf{x}_s^0,\mathbf{x}_g^0,t_0;\mathbf{k}_s,\mathbf{k}_g,\omega\right)=\int p_w\left(\mathbf{x}_s,\mathbf{x}_g,t\right)e^{i\omega t-i\mathbf{k}_s\cdot\mathbf{x}_s-i\mathbf{k}_g\cdot\mathbf{x}_g}d^2\mathbf{x}_s d^2\mathbf{x}_g dt \tag{1}$$

where $p_w\left(\mathbf{x}_s,\mathbf{x}_g,t\right)$ is the windowed data

$$p_w\left(\mathbf{x}_s,\mathbf{x}_g,t\right)=p\left(\mathbf{x}_s,\mathbf{x}_g,t\right)w_s\left(\mathbf{x}_s-\mathbf{x}_s^0\right)w_g\left(\mathbf{x}_g-\mathbf{x}_g^0\right)w_t\left(t-t_0\right) \tag{2}$$

where W_s, W_g and W_t are windowing functions for sources, receivers and time, respectively. If the source window width W_s is zero, then we have the case of common source gather. Likewise, if $W_g=0$, we have the common receiver gather. If $W_s\neq 0$ and $W_g\neq 0$, we get beams. t_0 is the center of the time window and it is determined as the traveltime for waves from the source beam center $\mathbf{x}_s^0$ to the target then reflected back to the receiver beam center $\mathbf{x}_g^0$.

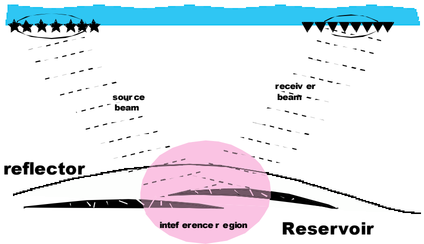

Figure 1. Interference geometry for double beams. Stars are sources and triangles are receivers. The pink ellipse indicates the interference zone within which the fracture properties can be inferred.

The form of the beams can be taken as Gaussian beams (e.g., Cerveny, 1982). If the beam widths are infinite, then we have plane wave extrapolation such as the double-square-root operator, plane wave migration, offset plane waves etc. The local angle information for waves is essential to perform the illumination correction. The double-beam stacking is a phase-space method and it simultaneously possesses both space and wavenumber properties of the wavefield.

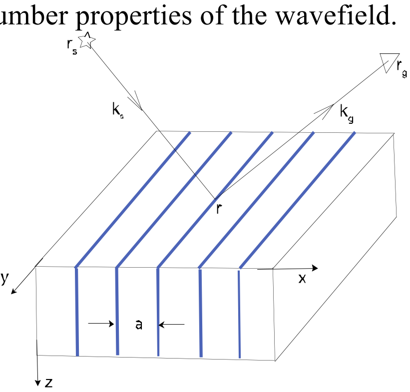

Figure 2. Schematic showing scattering by a set of parallel fracture. Fracture planes are vertical and parallel to the y direction.

It has been recognized that the Born approximation is good for understanding the interference patterns shown. Assume we have a set of vertical fractures that are equally spaced along the x direction and let a plane wave be incident upon the fractures from above (Figure 2). The incident field upon the fractures is $\exp\left[i\mathbf{k}_s\cdot(\mathbf{r}-\mathbf{r}_s)\right]$ and the scattered field at wavenumber $\mathbf{k}_g$ is

$$u_{scatt}\left(\mathbf{k}_g,\mathbf{k}_s\right) \propto \iiint_V \epsilon(\mathbf{r}) e^{i\mathbf{k}_s\cdot(\mathbf{r}-\mathbf{r}_s)+i\mathbf{k}_g\cdot(\mathbf{r}_g-\mathbf{r})} d^3\mathbf{r} = \tilde{\epsilon}\left(\mathbf{k}_g-\mathbf{k}_s\right)\exp\left[-i\mathbf{k}_s\cdot\mathbf{r}_s + i\mathbf{k}_g\cdot\mathbf{r}_g\right] \tag{3}$$

where ϵ can be thought as the scattering function caused by fractures. Assuming the fracture system is periodic along x and the spacing between two adjacent fractures is a. The scattered wavenumber and the incident wavenumber is related by

$$\mathbf{k}_g = \mathbf{k}_s + n\frac{2\pi}{a}\mathbf{e}_x, \quad n = 0, \pm 1, \pm 2, \cdots \tag{4}$$

where $\mathbf{e}_x$ is the unit direction along the x axis. When $n=0$, it is the specular reflection which corresponds to the common-mid-point (CMP) stacking. Many seismic studies use CMP stacking to infer fracture information. Since the fracture spacing a and its orientation $\mathbf{e}_x$ are completely eliminated when $n=0$, inference of fracture properties using CMP stacking should not be recommended in the context of scattering, i.e., the fracture spacing is comparable to the wavelength. $n=\pm 1$ corresponds to the forward or backward scattering. For typical seismic exploration applications, $|n|\geq 2$ is less interesting because the scattered wavenumber is likely to be in the evanescent regime. It has been observed by f-k analysis that the backscattered energy is the strongest

(Zhang *et al.*, 2006; Grandi, 2008). So in the following numerical example, we only consider the backscattering. By varying the fracture spacing a and its orientation, we effectively stack the seismic data along different moveout curve using equation (1).

Examples

To validate our idea of using our double-beam stacking to infer fracture spacing and orientation, we test our methodology on a synthetic dataset. The 3D model (Figure 3) contains a reflecting interface, which separate the upper and lower media. In the upper medium, $V_P = 2500$ m/s, $V_P / V_S = 1.6$ and $\rho = 2000$ kg/m^3; and in the lower medium $V_P = 4000$ m/s, $V_P / V_S = 1.6$ and $\rho = 2300$ kg/m^3. The source time function is a Ricker wavelet with the central frequency 40 Hz. The receivers are in a rectangular domain on the surface and they span from $x = 200$ m to $x = 2300$ m every 20m and from $y = 200$ m to $y = 3500$ m every 20m. Six sets of vertical fractures are placed in the lower medium in the depth interval between 1300m to 1380m. The fracture spacing and orientation are different.

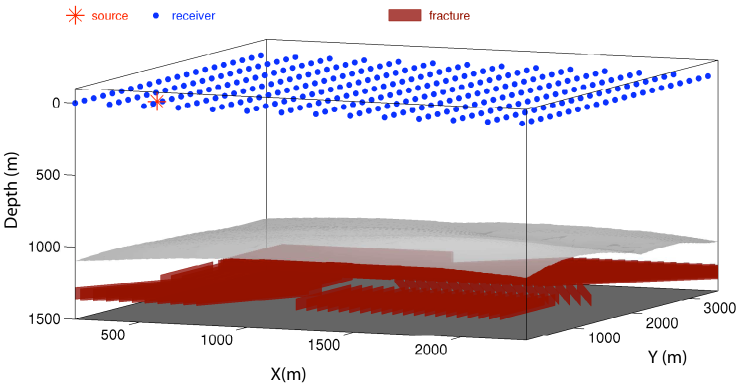

Figure 3. Fracture model in the numerical example.

To model seismic wave propagation through fractured media, we adopt the linear-slip boundary condition proposed by Schoenberg (1980): the traction is continuous across the fracture surface but the displacement is discontinuous. The normal (or tangential) displacement discontinuity is related to the normal (or tangential) traction by normal (or tangential) compliance. This validity of this boundary condition to model wave-fracture interaction has been supported by a series of laboratory experiments (Pyrak-Nolte and Cook, 1987). In the numerical simulation, we use Coates and Schoenberg's (1995) finite-difference effective medium method to simulate fractures with linear-slip boundaries. In this model, the thickness of fractures is assumed to be infinite small and their elastic properties are determined by the fracture compliance. In our simulation, the fracture tangential and normal compliances are equal to 10^{-9} m/Pa, which represents gas-filled fracture. As a proof of concept, we pick two targets at depth 1320m. The target A is at (x, y) = (1750m, 1700m) and the target B is at $(1750m, 750m)$. The receiver beam width is 150m and the source beam width is also 150m. The source beam center is at (1200m, 800m). In the double beam stacking, we use frequency of 60 Hz. The fracture spacing is same (a=50m) for both localities. The orientation of the fracture symmetry axis at the target A is 20 degrees and at target B it is 0 (or 180) degrees with respect to the x-axis. Our double-beam method is able to recover the fracture spacing and orientation for target A (Figure 4a) and target B (Figure 4b).

Conclusions

We have introduced a *double-beam stacking* method, in which the interference of two beams produces a characteristic pattern that depends on fracture spacing and orientation. The method is a phase-space method where point-source field and the plane-wave field are special cases. The method is adaptive for all kinds of acquisition geometry. We calculate the incident wave vector from the source to the target and then compute the backscattered wave vector based on the scattering theory and then stack the energetic backscattered seismic data. It works best when the wavelength and the fracture spacing are comparable. In this case, the common CMP technique cannot yield information on the fracture spacing and orientation. For typical seismic frequency bandwidths (10s Hz) and velocities (1000s of m/s), our method should be able to yield fracture spacing information on the order of 10s of meters for P-to-P scattering. However, if we use P-to-S scattering, much smaller spacing can be recovered and the stacking technique is same as for the P-P case.

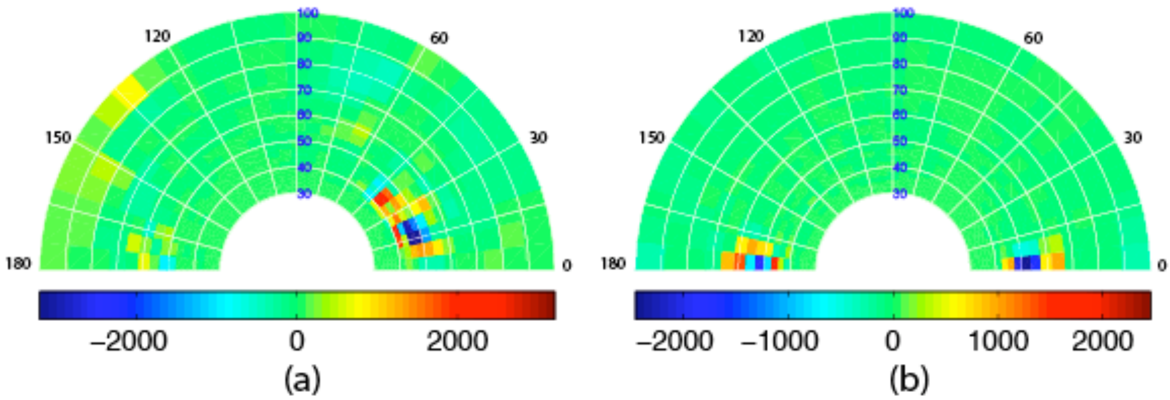

Figure 4. double-beam stacking results at target A (a) and B (b) as a function of fracture spacing (radius) and orientation. The orientation is for the symmetry axis of the fractures measured CCW with respect to the x-axis. The fracture spacing is measured in meters.

Acknowledgements

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