Modeling of inclined fracture network and calculation of fracture effect on seismic signal spectrum

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Abstract. The paper considers modeling technique for the medium with a network of inclined fractures and calculations for completing seismic tasks for such a medium. The network of plane-parallel fractures has controlled dip angle and fluid saturation. The time section for a model with water-saturated fractures is produced. The comparison of incident and transmitted signal spectra is made.

Introduction
Oil and gas reservoirs are known to constitute structurally heterogeneous geological formations which consist of a solid matrix and voids filled with fluid. The void space structure determines reservoir properties which are considered while choosing the optimal technique for reservoir development. The algorithms of land seismic surveys and borehole seismology are being currently developed to obtain more accurate and reliable information concerning the formation microstructure and spatial distribution of formation parameters. The resolving power of seismic methods provides generalized information about the effect of inhomogeneities on a wave field. Despite the fact that physical mechanisms of elastic wave interaction with inhomogeneities of different types and dimensions are investigated to a great extent, the complexity of internal structure of existing rocks makes it necessary to apply simplifying assumptions. In particular, when wave propagation through a rock is described the medium is assumed to be homogenous with “effective” acoustic properties [6]. The influence of inhomogeneities on a total wave field is revealed through the difference between characteristics of an effective model and those of integral solid matrix without void space.

The development of underexplored oil-gas bearing formations of Paleozoic period is a prospective area to increase mineral raw material base of West Siberia. Paleozoic deposits are mainly composed of carbonated rocks characterized by a complex cavernous-porous- fractured reservoir type [5]. Moreover, it was proved that the characteristics of a wave field are significantly dependent on tiniest fractures «opening» of which is measured by first micrometers, while the dimensions are sufficiently smaller than those of first Frenel zone section [1]. Microfracture size and shape are major factors which influence field formation of scattered waves when they propagate or reflect (are scattered) immediately off the specific surface of fractured formations.

Method and model description
Physical modeling is one of the most widespread approaches which are applied to deal with the issue. Installations for investigation of samples with various fracture networks are made. A wave field produced by such networks is detected and analysed [4]. For instance, the effect of reservoir fracturing
on a seismic wave has been studied since 1987 in the Laboratory for Applied Experimental Geophysics at Purdue University, USA, and over 30 articles were published in different periodicals.

However, it should be noted that physical modeling has a number of disadvantages. They are difficulty of parameter measurements, low flexibility of technique and technology, as well as distortions and limitations caused by equipment. It is possible to avoid these effects by using modern mathematical modeling. Nevertheless, one should consider that the accuracy of synthetic traces depends on appropriateness of a chosen medium model and on completeness of the equation system used to describe the propagation of all known wave types. The given paper considers the model of hypoeelastic wave described in [2, 8] where its similarity to an actual geological medium is shown. The calculations are performed using the finite-difference method which is also applicable to cope with forward seismic tasks for various medium models. This method is proved to be useful as a result of comparison of theoretical ray surfaces and data of numerical modeling.

The necessary stage of any modeling is comparison of calculated data with the real one. In the given research the input parameters are sample characteristics which are listed in [4], which gives a detailed description of installation and the procedures of the physical experiment, the obtained results are further compared. The sample used in the experiment is an aluminum bar, in which 20 fractures are sawed using 3 mm spacing. This arrangement is approximately equal to a quarter wavelength produced using the frequency of 0.5 megacycles. Figure 1 shows the acoustic wavefront recordings obtained from the intact sample F0 (a), and the fractured samples F3 one of which is dry (b) and the other is water-saturated (c).

Based on the sample description, the mathematical model the parameters of which coincide with data of the physical experiment was produced. The seismic fields which propagate through the fracture network were calculated. The model of a medium with dry fractures is given in figure 2a. Figure 2b is obtained when the parameters of water fluid are taken into account. Considering the unsaturated model in both experiments it is possible to observe the absence of distinct phase alteration, time-dependent wave diffraction. Provided that water is present, the images of seismic fields are also similar. There are quite distinct trace amplitudes which are more clearly expressed in the central zone than at the margins.

Considering the technique for carrying out the physical experiment one may notice that the installation construction makes it possible to arrange fractures parallel to one of its axes (vertical or horizontal cuts). In a real medium, tectonic stress causing rock discontinuity changes parameters of layer occurrence, consequently, fractures are located at an angle to the surface. Mathematical modeling can help to consider this peculiarity and produce models with inclined fractures.

We developed the generator of models with controlled dip angles and fracture saturation parameters. For the range of dip angles from the first semi-quadrant $0 \leq \alpha \leq \frac{\pi}{4}$ it is convenient to use the following formula for determination of current coordinates of computational cell in the source section.

\[
x_c = x \cos(\alpha) + w, \\
y_c = x \sin(\alpha) + w + (N - 1)h
\]  

(1)

Where $\alpha$ is a dip angle of a directional vector of a fracture network to the axis OX, N- number of fractures, h – fracture spacing, w – thickness of an individual fracture. The latter two parameters are determined by cell units. For the angles from the range $\frac{\pi}{4} \leq \alpha \leq \frac{\pi}{2}$ fractures are drawn not from the axis OX, as it was done in the formula (1), but from the axis OY. According to vertical seismic profile data the angle of 20° is significant angle for the analysis of weakness tangent lines [7]. Therefore, it is used for the development of model for inclined fractures (figure 3).
Figure 1. Time section obtained as a result of physical experiment: a) an intact sample, b) dry fractured sample, c) a sample with water-saturated fractures

Figure 2. Synthetic time section with the same parameters: 2a) dry fractured sample model, 2b) water-saturated fractured sample model

Figure 3. The model of a medium with network of inclined fractures: 1 – host medium, 2 – fluid in the fractures.

The figure shows that the represented model contains 22 fractures the thickness of which is 3, the spacing is 5 (see the formula 1). The host medium parameters correspond to average values for a terrigenous section; in particular, \( Vp = 3000 \text{ m/s}, \ Vs = 2000 \text{ m/s}, \ \rho = 2000 \text{ kg/m}^3 \). There are the following fluid parameters: \( Vp = 1500 \text{ m/s}, \ Vs = 0 \text{ m/s}, \ \rho = 1000 \text{ kg/m}^3 \). They correspond to characteristics of water (shear velocity component does not occur in a liquid medium). For this model the time section covering plane-wave incidence, excitation and its recording on OX line was calculated. The original seismic wavelet was calculated using Riker formula [3]:

\[
\hat{U}_y|_{CB} = F(t) = -2\pi f \sqrt{\rho} (t - t_0) \cdot e^{-2\pi f (t - t_0)^2},
\]

where \( \hat{U}_y \) is -drift velocity Y component. This impulse is characterized by smoothness of function, its derivatives and spectrum.
Results
For modeling the entire medium is supposed to be perfectly elastic, whereas in the fracture surroundings, i.e. in the zones of stress concentration, it is accepted to be elastoplastic [9]. The fragment of the obtained section is given in figure 4. Figure 5 shows the comparison of Fourier amplitude spectra of incident signal and wave transmitted through the fracture network.

![Synthetic time section](image)

**Figure 4.** Synthetic time section. An individual trace is distinguished.

![Spectrum of incident signal and transmitted signal](image)

**Figure 5.** Spectrum of incident signal and transmitted signal: 1 – original signal spectrum, 2 – transmitted signal spectrum.

The analysis of spectra reveals visual displacement of carrier frequencies to a low-frequency zone of spectrum and bandwidth reduction for both saturated and unsaturated fractures [8]. Furthermore, the similar regularities in spectrum transformations are observed through physical modeling [10]. In the right section of the curve it is indicated that the drastic decrease of total share of high frequencies causes increase of effect of individual high frequency bands affecting both diffraction characteristics for the entire fracture network and individual fracture vibrations.

The performed calculations indicate that general attenuation of high frequencies of spectrum which is revealed for a wave transmitted through a fractured unit results from the impact of acoustic impedance (if the effect of friction mechanisms is excluded). In its turn, this effect is connected with a set of heterogeneous surface waves which occur at the interfaces. The detected regularities can be further applied to reveal zones of absorption in seismic sections taking into account fracture network orientation through the analysis of seismic attributes.

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