THE EXPERIMENT RESEARCH FOR SONIC LOGGING NUMERICAL MODEL AND PHYSICAL MODEL IN FRAC-TURED TIGHT SANDSTONE RESERVOIR

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It is difficult to effectively discern the microfractures by methods of conventional logging and imaging logging, because the width of fractures in fractured tight sandstone reservoirs are less than 100μm, and the research about such kind reservoirs is relatively few in present condition. So, The research and experiments for sonic logging numerical model and physical model in fractured tight sandstone reservoir are launched.

The research of numerical simulation are applied in the methods of three-dimensional staggered grid stress and speed finite difference to make numerical value simulation for the problems of borehole acoustic field. The problems is aroused by point source in layer of elastic media and pore media of containing inclined thin cracks. The method can identify and evaluate effectively microfractures in fractured tight sandstone reservoir by using of parameters of stoneley wave energy amplitude and etc.

Physical model experiment research include small core experiment and model well, the experiment of small core is mainly to record and calculate waveform in different crack through the CTS - 8077 pultrasonic pulse/receiving apparatus. Plastic film sandwiched between two cores, the fracture width was controlled accurately at micron level by the adjustment of the thickness of the plastic film. Model well experiment is based on the principle of similarity, the scale of well model is 1 : 10. Then to use a magnifying glass to scale fracture width (100 times with a reading light microscope (with scale 1DIV/0.02mm)), measure waveforms at different fracture width through sonic transducer.

According to the results of numerical simulation and physical model show that waveform amplitude are very sensitive and diminish rapidly with the change of crack width due to the fractures width Which are less than 100μm. So, fracture width can not be determined quantitatively when the fractures width are less than 100μm.

Key words: Full wave train acoustic logging; Stoneley; P-wave; S-wave; Fractured tight sandstone; Numerical model; Physical model; Logging response characteristics

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Fractured reservoir has become one of the main targets for hydrocarbon exploration with the development of the world's oil and gas exploration. It is difficult to determine how fractured strata influence the waveform array sonic logging, for the crack width in the formation is generally narrow and the positional relationship between the well wall and fracture are uncertain, often multiple fractures are together to constitute the fracture zone. All these problems make the identification and evaluation of fractured formations become one of the problems at current logging industry. The methods of conventional logging and imaging logging are difficult to effectively identify micro-cracks, due to crack width of tight sandstone reservoir is generally less than 100μm. To this end, the author carried out a sonic experiment and numerical simulation of micro-cracks in the tight sandstone.

1. 1 Numerical simulation of sonic logging response based on Finite Difference Method

Hornby (1989) studied the propagation and reflection of stoneley wave by using plate-shaped crack model and low frequency analytic formula when it through the single fracture. Tang (1990, 1993) made the similar research, and pointed out that the stoneley wave will be produced at penetration zone. Sudhish Kumar Bakku (2013) also did a research about borehole acoustic field in cracks, but almost all of these methods assumed axially symmetric. Spring and Dudley (1992) and Kostek (1998) calculated field borehole acoustic field by using integral equations and finite difference method. Pawel J. Matuszyk (2013) adopted the finite element method to simulate the fractured borehole acoustic field. Guanwei applied finite difference method to calculate borehole acoustic field at horizontal layered porous media formations. But their calculations were for the two-dimensional conditions and width of horizontal layers and crack are large. It is commonly adopted the finite difference method to simulate borehole acoustic field at the seismic wave simulation problems, because the finite element method is more time-consuming than finite difference method. Three-dimensional staggered grid finite difference method was applied in non-axisymmetric problems of numerical simulation about highly deviated wells, tilt layered strata and anisotropic formations, and the results are effective, but the method are rarely used at borehole acoustic field of non-axisymmetric crack formation. To solve the problem, the research adopted three-dimensional irregular staggered finite difference method to do numerical simulation for formations which are inclined, thin fractured, porous at borehole acoustic field, and observed the borehole acoustic field characteristics under different cracks and formation parameters conditions. It lays a foundation for further research about using borehole acoustic information to have an inversion of fracture parameters.

1.1 Physical Model

Three-dimensional staggered grid force-speed finite difference method was taken in the research. The method numerically simulated the borehole acoustic field problems which causes by point source at containing inclined thin fractured porous formations. Figure 1 is borehole acoustic field.
Field diagram of containing inclined fractured formations. The research assumed that the sound source is located at the origin of a Cartesian coordinate system, well -axis coincides with z-axis, the cracks formed at outer wells are perpendicular to the plane with xz axis, and are composed of plane inclined α with xy axis, the distance between the intersection of fracture down-interface and the z-axis to origin are d. The vertical thickness of the cracks is H, the interval of fracture is h.

![Diagram](image)

**Fig 1** The borehole model in inclined fracture formation

### 1.2 The processing of variable grid finite-difference

Because the cracks being calculated are thin, and influenced by the size of borehole, if the small grid was calculated, it would result in calculation speed being too slow and even incalculable. So, a nonuniform grid approach was used at small grids of cracks, Large grid are used at the non-crack, and can greatly reduce the amount of computation and ensure the accuracy and improve the computing speed. Grid spacing changes may lead to the emergence of numerical reflection when a variable grid was used, the reason is that the phase velocity is a function of grid spacing after a scattered wave field. When the phase velocity gradient is larger, even if there is no change in speed and density, the incident wave energy will be reflected back partly and result in a numerical reflections. Although calculus of interpolation of the wave field on the area of grid changes can suppress the numerical reflection to some extent, but interpolation algorithm are large, and the results are not satisfactory. Therefore, the study did not use calculus of interpolation. Algorithms used in this research are according to step changes corresponding to the points to calculate the differential coefficients. The method does not produce numerical reflection and reduces the amount of computation.

### 1.3 Verify the correctness of the algorithm

When outer well is non-fractured porous media, compare the result of finite difference method with real axis integration, the results are shown in Figure 2. A sound source frequency is 2.5kHz. The distance between receiver and sound source is 1m. The black line in Figure 2 is the results of the finite difference method, the red line is the result of real axis integration. Results of two methods are basically consistent with each other and prove the correctness of the finite difference method. The magnitude of the difference in figure is caused by the normalization and does not affect the results of the study.

### 1.4 The detailed calculation results and analysis

The study simulates acoustic logging response characteristics of the porous medium formation (2%, 4%, 6%, 8%, 10%, 12%) under different porosity

#### 1.4.1 Stoneley wave

The summary figure for width of fractures and amplitude of stoneley wave under different porosity are shown by figure 3, when the frequency of porous media formation is 5kHz. From the figure, with the increase of crack width, Stoneley wave amplitude show a significant downward trend, and when the crack width is small (crack width <100μm), the waveform amplitude diminish
rapidly, wave attenuation are more obvious. The attenuation of waveform is more obvious; the larger porosity, the smaller Stoneley wave amplitude when it is under the same crack width.

**Fig 2** The comparing results of finite difference method and the real axis integration

**Fig 3** The relationship diagram of between the amplitude of Stoneley wave in in porous media formation and fracture width

The summary figure for width of fracture and Stoneley wave attenuation coefficient under different porosity is shown by figure 4, when the frequency of porous media formation is 5kHz, from the figure, with the increase of crack width, the Stoneley wave attenuation coefficient of different porosity shows a significant upward trend; the larger porosity, the larger the Stoneley wave attenuation coefficient. We can find that Porosity has a greater impact than Stoneley wave attenuation coefficient in porous media. The curve of Stone attenuation coefficient and crack width are more difference under different porosity.

**Fig 4** The summarized relationship diagram of Stoneley wave attenuation coefficient with crack width in porous medium

1.4.2 s-wave

Figure 5 is a summarized diagram which indicates a relationship of S-wave amplitude and porosity when porosity media formations are under different angle. From the figure, as the porosity increases, the amplitude of s-wave decreases gradually; under the condition of the same porosity, the greater the inclined angle, the greater the amplitude of s-wave.

2. Measurements of sonic experiments for rock of fractured reservoir

The experimental part of the research is composed by the experiments model well and small core two parts.
2.1 Model wells

2.1.1 The design of model well

According to the similarity theory, downsizing borehole and transducers (10 times) and increasing the Sound source frequency 10 times to simulate propagation of the actual wells of elastic wave in the experiments. The actual deepth of well and stratigraphic thickness of the well wall can be regarded as infinite comparing with Acoustic system size. Putting quartz sandstone cores into the laboratory sink to measure.

2.1.2 Artificial fracture

The experiment of model well fracture depend on manual control, grind smoothly the section of well model and firmly affix together, scale the width of fracture with magnifier (100 times with a reading light microscope (with scale 1DIV/0.02mm)). It could measure waveform at different crack width through the adjustment of crack width by manual and machine. The smallest crack width of well model can reach 100μm.

2.1.3 Detailed experimental test results and analysis

The waveform diagram of sandstone 3 probe (frequency 50kHz) variable spacing and stationary spacing 23 are indicated at figure 6 and figure 7, the fracture width is 0.3mm. The figure shows source distance becomes longer, wave of time becomes longer, the waveform amplitude smaller; When sound of the probe come through the cracks, the amplitude of Waveform get smaller obviously. Other probe waveform (frequency of 100, 150 kHz) consistent with the 3rd probe waveform.

2.2 Small core

2.2.1 Key technologies

The relationship between P and S-wave amplitude and the cracks was studied by the methods of measuring and recording the model waveform at different cracks and calculating the arrival time of S and P-wave and recording the wave amplitude in the same time. The difficulty of experiment is the width of fracture should be controlled at the micron level, the solution is "Artificial cracks technology". The core principle is that the two similar property cores are sandwiched together by the core holding unit. Plastic film sandwiched between two cores, the fracture width was controlled by the adjustment of the thickness of the plastic film. The smallest fracture width of small core are 30μm.
2.2.2 Experiment of Materials

Natural cores used in the experiment were taken from the Tarim Basin Dabeikeshen well area. Two core which had similar porosity and permeability were selected in a group. Selected core were 10, and divided into 5 groups. The length of cores were measured directly by calipers.

2.2.3 Detailed experimental test results and analysis

1) P-wave amplitude. The relationship diagram of P-wave amplitude and fracture width which was collected from the cores of 5 groups is shown in figure 8. From the figure we can observe that attenuation of waveform is more obvious and waveform amplitude rapidly diminish when fracture width is getting smaller (width of fracture <100μm). Waveform amplitude get stabilized when fracture width is getting larger.

2) S-wave amplitude. The relationship diagram of S-wave amplitude and fracture width which was collected from the cores of 3 groups is shown in figure 9. From the figure we can observe that the more lager porosity, the smaller S-wave amplitude. Waveform amplitude get stabilized when fracture width is getting larger. Comparing with the change of P-wave amplitude, the attenuation of s-wave amplitude are more obvious.

3) Attenuation coefficient of P-wave. The relationship diagram of attenuation coefficient of P-wave and fracture width which was collected from the cores of 3 groups is shown in figure 10. As can be seen, the greater the porosity, the greater the attenuation coefficient of the P-wave.

4) Attenuation coefficient of S-wave. The relationship diagram of attenuation coefficient of S-wave and fracture width which was collected from the cores of 3 groups is shown in figure 11. As can be seen, the greater the porosity, the greater the attenuation coefficient of the S-wave.
3. The comparison result of numerical simulation and the measurement of small core

The result of numerical simulation of grid porous media formations borehole acoustic field were compared with the actual measurement of small core (Fig 12). As can be seen, the result of numerical simulation of porous media has a higher compliance with the measurement result of small core.

Fig 8 Five groups of relationship diagram of P-wave amplitude and fracture width from different core prospcy

Fig 9 Five groups of relationship diagram of S-wave amplitude and fracture width from different core prospcy

Fig 10 Three groups of relationship diagram of attenuation coefficient of P-wave amplitude and fracture width

Fig 11 Three groups of relationship diagram of attenuation coefficient of s-wave amplitude and fracture width

Fig 12 The comparison diagram of numerical simulation and the measurement of small core.
Comparing the numerical simulation results of porous media with the simulation results of small core, waveform amplitude is very sensitive with the change of fracture width and diminish very quickly when fracture width are less than 100 μm. So it can not be determined the width of fracture when fracture width are less than 100 μm.

4. Understanding and suggestions

Through the methods of numerical simulation and physical experiment, we simulated a lot of fractures which are at micron level (the minimum of fracture width is 20 μm) and at different angle, analyzed the relationship between waveform amplitude and attenuation coefficient and crack width and porosity, made a physical model experiments for a single micron-sized cracks (the minimum fracture width of model wells are 100 μm, the minimum fracture width of small cores are 30 μm), analyzed the relationship between waveform amplitude and attenuation coefficient and crack width and porosity. When the sound probe get through the cracks, waveform amplitude is smaller. When sound probe get through different width of fractures, the larger fracture width, the smaller waveform amplitude. When fractures width are smaller, the waveform amplitude diminish quickly, the waveform amplitude is sensitive with the change of fracture width. According to numerical simulation results and experimental results of the physical model, it is thought the waveform amplitude is sensitive and diminish quickly with the change of fracture width as fractures width are less than 100 μm. So the fracture width can not be determined when fractures width are less than 100 μm. When the crack width become larger, longitudinal waves, shear waves, Stoneley wave amplitude are reduced, the attenuation coefficient increases; if other parameters remain unchanged, the greater porosity, the greater P-waves, S-waves, the Stoneley attenuation coefficient; The fitting formula which indicates the relationship between P-waves, S-waves, the Stoneley attenuation coefficient with fracture width can be given under different porosity. The use of fitting formula can find fracture-developed zone by the methods of attenuation coefficient to inverse crack width.

REFERENCES: