Study on Processing Method of Acoustic Emission Signal for Hydraulic Fracture Measurement

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Abstract. Hydraulic fracturing has become a key technology for the unconventional oil and gas development. Due to the complexity of geological conditions and the limitation of monitoring technology, it is still very difficult to accurately understand the three-dimensional distribution characteristics of hydraulic fractures. Based on the acoustic emission monitoring and three-dimensional laser scanning for large scale (762 mm * 762 mm * 914 mm) hydraulic fracturing test, hydraulic fracture morphology characterization is measured. The control method of acoustic emission signal quality based on amplitude, root-mean-square phase and multi-channel contrast signal recognition was explored. A multi-parameter constrained grid search and location method was established, which significantly improved the location accuracy and realized the dynamic and static real-time characterization of hydraulic fracture space expansion under indoor conditions. The results show that: based on laser scanning technology, the detailed characterization method of hydraulic fracture morphology is established, and the fracture morphology in laboratory experiment can be improved from two-dimensional observation to three-dimensional display. Due to mutual influence of natural fracture and in situ stress field, the hydraulic fracture appears complex geometry such as turning and bifurcation. The accuracy of acoustic emission location is improved by 10\%, and the consistency with the actual fracture scale reaches 95\%. The processing method of acoustic emission signal in this paper can be directly used in the optimization of field microseismic monitoring to guide the evaluation of unconventional reservoir stimulation, which shows a broad application prospect.
1. Introduction

For more than half a century, hydraulic fracturing technology has always been an important engineering means for increasing oil and gas production\cite{1}. Especially in recent years, the great progress of horizontal well drilling and fracturing technology has brought the economic development of unconventional oil and gas resources worldwide, and the tools and equipment for reservoir stimulation have been significantly improved\cite{2}. On the other hand, due to the complicated geological conditions, the hydraulic fracture propagation mechanism is hard to be known clearly. The different reservoir and fracturing process would result in the diversity of fracture morphology. Therefore the accurate understanding on fracture propagation is a key link in the process of reservoir fracturing successfully.

For a long time, hydraulic fracture diagnosis methods have been innovated constantly. According to laboratory experiments, pilot filed trial, mine monitoring and other ways, the understanding of hydraulic fracture morphology are deepened\cite{3}. Since the 1960s, hydraulic fracturing experiment has been conducted to study the fracture expansion morphology. As the technologies are advanced, the scale of experimental sample is increasing from 10 cm to 100 cm, which improve the similarity between indoor and field greatly. The simulation technology for fracturing process is also innovated continually, from openhole completion, perforation stage to hydraulic jet fracturing completion, multistage fracturing. In regard to the fracture diagnosis, the traditional method is sample slicing after fracturing test in lab. Then acoustic emission technology, CT scan, laser scanning imaging and other advanced measuring technology are introduced. Starting in the 1980s, Warpinski conducted mine fracturing and roadway excavation. the results revealed the complexity of hydraulic fracture morphology firstly\cite{4-5}. In the recent years, many domestic and foreign oil companies have conducted drilling cores after fracture stimulation to observe the real fracture scale and the proppant migration. the above work have guided the optimization of fracturing design and well pattern deployment in their respective key unconventional block. In the 1990s, as the inclinometer and micro seismic diagnosis technologies were developed and applied in oil field, the understanding of the fracture morphology in field scale is further clear. In 2002, Mitchell put forward and confirmed the complex fracture network firstly in shale gas reservoir using microseismic and slic water fracturing that opened the prelude of the shale gas revolution. In the recent years, the near-wellbore diagnosis technologies such as well temperature test, optical fiber test (DAS, DTS), tracer test and other methods have developed rapidly due to their reliable accuracy and simple construction, but their disadvantages such as high cost and limited monitoring range are also obvious\cite{6}. Therefore, microseismic monitoring, as the mainstream field diagnosis technology, is still widely used.

In 1962, Mogi first started the study of two dimensional acoustic emission location under the condition of rock bending and deformation\cite{7}. In 1968, Scholz studied the three-dimensional spatial location based on acoustic emission events\cite{8}. In 1996, Delft University in the Netherlands applied ultrasonic monitoring technology in fracturing experiment\cite{9}. However, this technology is capable of two-dimensional plane positioning and is insufficient to describe the three-dimensional morphology of fractures. Later, as the development of acoustic emission equipment and positioning technology, acoustic emission monitoring technology can process passive signal data in the rock physical simulation in real time and conduct three-dimensional space positioning. At present, micro-seismic monitoring technology is mainly used to evaluate the shape of hydraulic fractures in underground when hydraulic fracturing is carried out in various oil fields\cite{10}. Micro-seismic/acoustic emission positioning technology is becoming the most critical technology in nowadays. The most basic positioning method is time difference positioning, based on which relative positioning method, Geiger positioning method, least square method, etc. are developed. Hu Xinliang et al. used relative positioning method to improve the reliability of acoustic emission positioning results\cite{11}. Aiming at the problem of accuracy in the acoustic emission time difference positioning algorithm of rock mechanics, Huang Xiaohong proposed a new rock acoustic emission source positioning method with full phase and Geiger algorithm to accelerate the convergence speed\cite{12}. With the improvement of algorithm adaptability, microseismic/acoustic emission technology has been widely used in physical model test and fracturing monitoring.
To sum up, although the fracture diagnosis technologies are developed constantly from lab to field, it is still hard to satisfy the requirement of fracture morphology evaluation accurately. Due to the natural fracture development and unconventional reservoir heterogeneity, the acoustic emission and micro seismic data acquisition and positioning are difficult. So the further experiments and optimization methods such as theory research should be necessary to enhance the level of fracture monitoring technology. In this paper, based on the hydraulic fracturing physical simulation experiments with large scale natural rock and the introduction of laser scanning imaging technology, the acoustic emission monitoring technology optimization is studied referring to the acoustic signal quality control and precise positioning method. The research results is applied to the micro seismic monitoring, which would powerfully boost the efficient implementation of reservoir stimulation technology.

2. Experimental Technology

2.1. Large Scale Fracturing Experiment with Acoustic Emission

Physical simulation experiment technology of hydraulic fracturing has always been recognized as an effective research method to understand hydraulic fracture morphology and study fracture initiation and propagation mechanism. Fracturing experiments are conducted with natural or artificial rock sample, and combined with imaging techniques such as acoustic emission, CT scans. The traditional experimental samples are the cube shape with the scale ranging from 10-40cm, but there are also obvious disadvantages of boundary effect and fracture initiation effect. So Fu Haifeng built the largest scale sample loading system (762 mm * 762 mm * 914 mm) for hydraulic fracturing in lab. According to the experimental tests, many research areas can be carried out as follows: fracture initiation, unconventional fracturing, acidizing, perforation and wellbore stability. The experimental system mainly consists of stress loading frame, confining stress system, wellbore injection system, control system and acoustic monitoring system, as shown in Figure 1. The confining stress system can load three principal stresses on rock independently, with the maximum loading pressure up to 69MPa. The wellbore injection system can realize multi-stage continuous pumping pre-fluid, sand-carrying fluid and displacement fluid alternately, and also can simulate special pumping processes such as fiber temporary plugging fracturing and slug sand fracturing. The real-time control system can record the data of pressure curve, pump injection rate and confining pressure in real time, and also can control the pump injection rate and pressure in real time. The acoustic emission system can realize the real-time location of acoustic events in the hydraulic fracture propagation to achieve the purpose of fracture morphology measurement.

![Figure 1 Large scale fracturing test system.](image)

During the fracture propagation, the rock particles cementation state is destroyed. It would be accompanied by a large number of acoustic emission events. Then multiple acoustic probes embedded in the rock surfaces would receive the acoustic waves. By the analysis of acoustic emission events (AE) distribution, the fracture front location corresponding to different time would be measured. Due to the different position of the embedded acoustic probes, the distance from the acoustic event is
different, which leads to the different traveling time for the same acoustic event. The coordinate data of the acoustic probe, the velocity data of the acoustic wave and the traveling time data can be used to calculate the coordinates and the time of an acoustic event. The passive acoustic positioning method adopts the uniform acoustic velocity model, which is suitable for the acoustic event positioning for fracture propagation in homogeneous rock samples. But for heterogeneous rock specimen, there is big difference between acoustic waves velocity in all the directions. The passive acoustic positioning method may exist big error. In addition, due to loose lithology or the existence of natural fractures, acoustic wave propagation attenuation in the rock sample is high, and effective acoustic wave signals cannot be received. Therefore, the acoustic monitoring technology has a great professional potential for improvement from data acquisition and positioning method optimization.

![Figure 2 Passive acoustic emission positioning schematic diagram and probe embedment](image)

The acoustic emission monitoring system adopts German Vallen Amsy-6 acoustic emission system. There are 24 acoustic channels, which can record continuous waveform signals in the frequency range between 1.6Khz and 2.4Mhz and more than 20 characteristic parameters, including acoustic event numbers, amplitude, energy and rising time, etc. 40MHz, 18-bit A/D converter can do the real-time analysis and further signal processing. The 24 SE150-M probes are used to receive acoustic emission signals. The bandwidth of the probe is 50-500khz, and the probe size is 20.2mm×20.2mm. The 24 probes are connected to 24 Vallen AEP4 type preamplifier, respectively. After the recorded signal is amplified by 30dB, it is input to the acoustic emission monitoring system. Then the acoustic emission parameters and waveform are recorded in real time by the acoustic emission system.

2.2 3D Laser Scanning Technology

Although the experimental system is equipped with advanced acoustic emission monitoring system, which can dynamically monitor fracture initiation and propagation in real time. Due to the limitation of positioning accuracy, it is impossible to depict the real fracture morphology completely. By injecting tracer or dye, the fracture morphology can only be recorded by simple photography instead of visual three-dimensional display. Some papers used CT technology to scan 30cm scale samples and reconstruct the 3D spatial morphology of hydraulic fractures. However, ray attenuation degree is sensitive to sample size, and high-power CT technology cannot realize the characterization of fractures in meter-scale samples. Based on the above reasons, in order to display the final shape of hydraulic fractures more objectively and accurately, three-dimensional laser scanning technology is introduced in this paper. By scanning the sliced samples after the experiment one by one, and reconstruction of the scanning morphology, the spatial scale and distorted morphology of fractures can be clearly displayed.

3D laser scanning technology is a new technology which has attracted more and more attention in domestic research. It is based on the principle of laser ranging. By recording the three-dimensional coordinates, reflectance and texture of a large number of dense points on the surface of the object, it can quickly reproduce the three-dimensional model and various map data such as lines, surfaces and bodies. Because the 3D laser scanning system can obtain a large number of data points of the target object, it is considered as a revolutionary technological breakthrough from the evolution of single point measurement to surface measurement. The laser scanning equipment used in this paper sends laser which wavelength of 660nm, field depth of 300mm, power of 35mW, sampling rate up to 18,000 points per second, and accuracy of 0.1mm. The collected information is divided into two parts, including point cloud data that is accurate position information and color photo information. The two parts are coupled to each other to form a complete set. The specific steps are as follows:
1. After fracturing test, prejudge the fracture distribution characteristics and determine the slicing direction. Then, sections are conducted at an interval of 50-100mm on the fracture propagation path.

2. Each section is labeled with a marker specialized for the 3D laser scanner. The marker is a black reflector and high reflectivity. Its layout can be selected according to the smoothness of the sample surface. Marking points should be randomly pasted. For the flat surfaces, the marker distance should be less than 100mm. Where the curvature is higher, the number of marks should be greater, and the marker distance should be less than 30mm.

3. After scanning all the slices, import the data of each slice into the reverse engineering software, such as Geomagic Studio 3D, and splice them into a whole rock block.

4. According to the fracture lines on the slice surface, create fracture data points quantitatively and draw fracture lines.

5. Splice and encapsulate each fracture line to create a complete fracture surface.

This method adopts non-contact optical measurement technology to directly obtain high-precision three-dimensional point data, which can scan rocks with different shapes and colors, and understand fracture morphology in a more intuitive, three-dimension way. It is not limited by environment and location, which is convenient for storage, display and analysis of fracture information after experiment. Compared to traditional test sample warehouse, the digital experimental core is more beneficial to long-term safety protection of experimental results.

3. Optimization of Acoustic Emission Location

3.1. Acoustic Signal Quality Control Method

The main measures to improve the acoustic emission signal quality are as follows:

3.1.1. Physical coupling of acoustic probe and rock

The fixing of probe and rock uses putty to consolidate. The putty and rock have different petrophysical properties. If the consolidation quality is poor, the probe is prone to jitter for a very short time when the signal is received. The "tail" effect will appear in the received AE waveform. Considering this difficulty of the effect elimination, the acoustic signal quality should be improved through fine consolidation operation to control the coupling between the probe and rock.

3.1.2. Digital signal processing methods

The acoustic emission signal frequency is relatively high in lab test, the acoustic interference is brought obviously by the experimental background. It can be suppressed by filtering according to the effective acoustic signal frequency band. Signal analysis methods such as amplitude, root-mean-square phase and multichannel comparison are used to improve the visual recognition of signals (as shown in the figure below). These methods can suppress noise and improve the SNR, but the original amplitude value will
be changed to different degrees. In general, the relative amplitude preserving method is used for noise suppression by selecting appropriate parameters.

3.2. Acoustic Positioning Method Optimization

3.2.1. Optimize the picking up time of acoustic wave
Because of the large acoustic emission signal data, ranging from tens G to hundreds G, it is difficult to pick up the receiving time manually. High-performance computer is needed to do that automatically. The methods for automatic seismic signal picking up or phase recognition include threshold method, energy ratio method, AIC algorithm, PAI/K method, neural network method, fractal dimension method, polarization analysis method and Kalman estimation. Threshold method is one of the fastest and most widely used automatic pickup methods. Threshold is set for data collection. When the energy exceeds the threshold, it is considered to be an effective AE signal, and the position beyond the threshold is considered to be the initial arrival time of the waveform. The disadvantage of this method is that the initial arrival time cannot be picked up accurately due to the influence of waveform peak. It is difficult to distinguish seismic signal from high-amplitude noise.

In this paper, according to the characteristics of AE in hydraulic fracturing, the long and short time window energy ratio combined with the earliest arrival time, the probe order of the arrival time was adopted to correct the incorrect pickup. In this method, the absolute value, energy and envelope of acoustic data in the anterior and posterior time windows are firstly calculated. Then the ratio of the anterior and posterior time windows eigenfunctions is calculated; If the ratio is greater than the preset threshold value, an effective seismic event is confirmed. This method avoids the influence of random large amplitude events on waveform picking up, and is better than amplitude threshold method (As shown in Figure 5).

Figure.4 Flow chart of effective AE signal processing method

Figure.5 Picking up the arriving time using multiple parameter constraints
3.2.2. Determination of the sample velocity field

By adopting the active acoustic detection method, a sensor actively transmits a pulse waveform and the other 23 channels receive the signal. Picking up the time difference could adjust the sample velocity, and then invert the position of the pulse signal. The pulse excited is by the first probe, which is adjusted through the picked up arrival time and that calculated by the velocity model. When the arriving time difference is the minimum, the sample speed is confirmed. In the same way, 72 active pulses can be fitted and adjusted for reverse positioning to return all the active pulses (figure 6). So the optimal sample velocity for acoustic emission positioning is confirmed finally.

![Figure.6 The acoustic velocity calculation](image)

3.2.3. Acoustic emission location algorithm

Almost all of the acoustic emission inversion methods start from the initial arrival travelling time, such as longitudinal and transverse wave time difference method, Gei ger correction method, three-point positioning method, diffraction superposition method, etc. The acoustic event location can be calculated according to the travel times of the direct waves in the same phase axis. This paper mainly adopts the multi-parameters constrained grid search to locate AE. When positioning space is gridded, the travelling time from different grid points could be calculated. Then they are fitted to the time that acoustic emission signals are picked up. Corresponding to the best fitting time, the grid point is the AE position. In the calculation process, the initial space position is determined according to the minimum arriving time. As the search space is reduced, the search time is shorten. Finally, the optimal grid points are refined and interpolated (as shown in Figure 7).

![Figure.7 The grid search algorithm for acoustic location](image)

4. Application

To verify the laser scanning method and acoustic emission accurate location optimization method, four large scale hydraulic fracturing experiments have been conducted with homogeneous and natural fracture sandstones. All the experimental samples were disposed by laser scanning to show hydraulic fracture spatial distribution. Considering the risk of sample breakage, only two experiments with natural fracture samples were monitored by acoustic emission. The test parameters are shown in table 1, the analysis results are shown in figure 8-11.

According to the analysis of the four tests, it is shown that the hydraulic fracture morphology varies greatly, which further confirms the complexity of real hydraulic fracture propagation.

In Test 1, compared with the actual fracture scanning, the grid search method with multi parameters constraints improves the acoustic emission location accuracy by 10%, in line with the degree of more
than 95%. Most of the acoustic emission events are relatively concentrated, which are located in the left side of the wellbore. It reflects clearly hydraulic fracture asymmetric propagation. This test validates the accuracy of the acoustic emission location method.

In Test 2, there are natural fractures distribution in the sample. Laser scanning shows that hydraulic fracture propagation is affected by natural fracture obviously. Injection fluid caused two natural fractures open. On the other hand, the acoustic events distributed around only the bottom fracture. there are less points at the upper fracture. So the density of acoustic events distribution should be related to the energy of natural fracture opening. Therefore, it can be seen that the acoustic location method still needs to be further optimized and improved for hydraulic fracturing in reservoirs with natural fractures.

In Test 3, the laser scanning shows that one horizontal fracture was initiated at the open hole section of the wellbore and one longitudinal fracture was initiated along the wellbore direction at the same time. According to the observation of cutting slices, the longitudinal fracture should be the opening of natural fracture or bedding. In other words, the hydraulic fracturing are controlled by the in situ stress field and the natural fracture or bedding together. The fracture geometry in the near wellbore is more complicated than the conventional understanding.

In Test 4, the experimental results further confirmed the complexity of the hydraulic fracture distribution in three-dimensional space. Affected by the natural fracture or beddings, one longitudinal fracture was initiated firstly along the wellbore. As the fracture was propagating, it was controlled by the in situ stress more obviously. The top tip of the fracture is deflected gradually to the horizontal direction and at the bottom tip, one horizontal fracture was initiated sharply which was propagating at the left and right sides of the longitudinal fracture. This similar experimental results also have appeared in Test 3.

| Test | $\sigma_v$, MPa | $\sigma_H$, MPa | $\sigma_h$, MPa | Pumping rate, ml/min | Viscosity, mPa.s |
|------|-----------------|-----------------|-----------------|---------------------|-----------------|
| 1    | 15              | 12              | 10              | 30                  | 5               |
| 2    | 10              | 12              | 5               | 60                  | 50              |
| 3    | 10              | 20              | 12              | 60                  | 1               |
| 4    | 10              | 20              | 12              | 60                  | 1               |

Figure 8. Test 1 results of acoustic emission location and laser scanning fracture in homogeneous sandstone
5. Conclusion
1. For the ultra-large scale (762 mm×762 mm×914 mm) hydraulic fracturing experiment, a new characterization method of hydraulic fracture morphology was established based on laser scanning technology, so as to improve the fracture depiction from two-dimensional to three-dimensional.

2. Laser characterization for the four experimental results show that under the combined affection of natural fracture and in situ stress field, hydraulic fractures appear complex geometry such as turning and bifurcation, which are greatly different from the conventional understanding.

3. One acoustic signal quality control method based on amplitude, root-mean-square phase and multi-channel contrast signal identification was explored. The multi-parameter constrained grid search and location method was also established, which significantly improved the indoor acoustic location accuracy. The two methods realized the dynamic and static real-time characterization of the hydraulic fracture propagation. The accuracy of the improved AE is increased by 10%, and the consistency with the actual fracture scale reaches 95%.

4. The methods for hydraulic fracture static characterization and dynamic propagation can be directly used in the optimization of field microseismic monitoring and interpretation technology, and guide the evaluation of unconventional reservoir stimulation. It is showing a broad application prospect.

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