Data Analysis of Hydraulic Fracturing Pressure in Unconventional Oil and Gas Fields

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Abstract. After the completion of fracturing construction in unconventional oil and gas fields, the phenomenon of water hammer oscillation in the process of pump stopping during fracturing construction will lead to the inaccuracy of reflecting the trend of pressure transformation and increase the difficulty of fracturing effect evaluation in the process of fracturing construction. Therefore, three filtering methods, Savitzky-Golay filter, FFT filter and wavelet transform filter, are used to calibrate the measured pressure in this paper. It is found that the method of wavelet transform can achieve the most ideal effect by comparing with the measured data. The field example of well X1 in Ordos Basin proves that the method of wavelet transform can accurately reflect the trend of pressure transformation. This method is of great significance to improve the evaluation of post pressure effect in the process of fracturing construction.

1. Introduction

After the fracturing of unconventional oil and gas fields is completed, there is often a section of pressure drop data, which conforms to the injection pressure drop seepage theory [1, 2]. Therefore, the well test analysis method can be used to analyze this section of data, so as to realize the rapid evaluation of the effect after fracturing. However, due to the water hammer phenomenon, the shut-down pressure data will have obvious low-frequency oscillation [3], the pressure data noise is large, which has a certain impact on the injection pressure drop evaluation, so it is necessary to study the noise reduction algorithm for the shut-down pressure data.

In this paper, Savitzky-Golay filter [4, 5], FFT [6] and wavelet transform [7] are used to denoise the pressure data of pump stop water hammer oscillation. Through the comparison and analysis of the denoising effect, the denoising algorithm of wavelet transform is selected. Research shows: After denoising with wavelet transform, the quality of pressure drop data is obviously improved, and the fracture parameter information contained in pressure drop data can be accurately extracted. The success of this study can greatly promote the popularization of injection pressure drop analysis technology of pump stop pressure drop data in oil field, which is of great significance to improve the speed and accuracy of post pressure effect evaluation and reduce the cost of post pressure evaluation.
2. Pump stop water hammer oscillation pressure signal

In the process of fracturing construction, in addition to supporting the artificial fracture, some liquid enters the formation through filtration, which is similar to the injection pressure drop of water injection well. Therefore, the injection pressure drop method can be used to analyze the pressure drop data of pump stop, so as to achieve the purpose of rapid analysis of fracturing construction effect.

However, due to the fact that there is often water hammer during the process of shutting in the well (Figure 1), the injection pressure drop analysis technology requires relatively smooth pressure data. Therefore, how to eliminate the water hammer signal in the injection pressure drop data is the key technology of the injection pressure drop analysis of the fracturing stop pump data. Through data analysis, the water hammer signal conforms to the characteristics of low-pass filtering signal. This paper investigates three kinds of low-pass filtering signal processing algorithms, and selects the denoising algorithm that conforms to the water hammer signal processing.

![Figure 1. Shut-in pressure drop data.](image)

3. Design method of staged fracturing in horizontal well

3.1. Pressure denoising based on Savitzky-Golay filter

Savitzky-Golay algorithm [8] is widely used in data flow smoothing and de-noising. It is a best fitting method based on Polynomials and least square method in time domain.

Savitzky-Golay smoothing formula is:

\[ X_{k,i} = \bar{X} = \frac{1}{H} \sum_{j=0}^{H} X_{k+i} h_i \] (1)

The purpose of multiplying each measurement value by smoothing coefficient \( h_i \) is to reduce the influence of smoothing on useful information as much as possible, so as to improve the disadvantage of smoothing denoising algorithm. \( h_i/H \) can be used for polynomial fitting based on the least square principle. The key of Savitzky-Golay convolution smoothing lies in the solution of matrix operator. Set the width of filter window as \( n=2m+1 \), and each measurement point as \( x=(-m,-m+1,\ldots,0,1,\ldots,m-1,m) \), \( k-1 \) polynomial is used to fit the data points in the window.

From Figure 2, it can be found that Savitzky-Golay filtering can effectively smooth the pressure curve after pump stop, there is a certain deviation between the filtered data and the original data in the pressure oscillation section.

![Figure 2. Comparison of the effect of Savitzky-Golay filtering on shut-in pressure drop data.](image)
3.2 Pressure denoising based on FFT

The sine wave $e^{i\omega t}$ used in the basis of FFT is the eigenvector of all linear time invariant operators, so any signal can be expanded into the superposition of several sine signals, that is to say, FFT is to transform the signal from time domain to frequency domain. For the known continuous signal $x(t)$, it can be expressed by the finite discrete sequence $x_n(n\Delta t)$ of the sampling interval $\Delta t$, where $n = 0, 1, 2, 3...N-1$. $N$ represents the length of the signal, so the DFT of the signal can be expressed as:

$$\hat{x}_m = \frac{1}{N} \sum_{n=0}^{N-1} x_n e^{-2\pi i mn/N}$$

(2)

Where $m = 0, 1, 2, 3...N-1$ is the frequency index. The number of times needed to calculate the Fourier transform directly through equation (2) is $N^2$, and the amount of calculation is very large. Later, Cooley and Tukey proposed FFT, which greatly reduced the amount of calculation, about $N/2\log_2 N$.

From Figure 3, it can be found that the Fast Fourier Transform can be used to deal with the extremely complex working conditions, although it will get the ideal results in the period of violent oscillation, but it will also cause false oscillation in the smooth section.

![Figure 3. Fast Fourier transform filtering effect comparison of shut-in pressure drop data.](image)

3.3 Pressure denoising based on Wavelet Transform

Wavelet transform can analyze the local characteristics of time-varying signals. In principle, problems that can be analyzed by Fourier transform can be replaced by wavelet transform.

![Figure 4. Time-frequency boxes of wavelets $\psi_n^s(t)$ and $\psi_{n0}^s(0)$.](image)

The continuous wavelet transform of a discrete time series $x_n(t)$ is as follows:

$$WT(s,t) = \sum_{n'=0}^{n-1} x_n^* \psi^s_{n'} \left( \frac{(n-n')\Delta t}{s} \right)$$

(3)

Where * denotes complex conjugation, $n'$ is the time translation, and $\psi$ is the result of dimensionless transformation of the parent wavelet $\psi_0$.

$$\psi \left( \frac{(n-n')\Delta t}{s} \right) = \left( \frac{\Delta t}{s} \right)^{\alpha s} \psi_0 \left( \frac{(n-n')\Delta t}{s} \right)$$

(4)
According to the convolution theory, Equation (4) can be converted into the inverse Fourier transform to calculate the product of $x_n(t)$ and $\psi^*$. 

$$\text{WT} (s,t) = \sum_{n=0}^{N-1} \hat{x}_n \hat{\psi}^* (s\omega_n) e^{in\omega t},$$

Where $\hat{\psi}(\sigma_n)$ is the Fourier transform of the parent wavelet, which can be expressed as:

$$\hat{\psi}(\sigma_n) = \left(\frac{2\pi s}{\delta t}\right)^{0.5} \hat{\psi}_n(s).$$

And $\hat{\psi}(\sigma_n)$ satisfies:

$$\sum_{n=0}^{N-1} |\hat{\psi}(s\omega_n)|^2 = N.$$

In order to realize the continuous wavelet transform with equation (6), the appropriate scale must be selected first. Generally speaking, the scale $s$ is selected by the binary method, that is, the scale is set to the fractional power of 2:

$$s_i = s_0 2^{\delta j}, \quad i = 0,1,2,...,J,$$

$$J = \frac{1}{\delta j} \log_2 \left(\frac{N\Delta t}{s_0}\right).$$

Where $s_0$ is the smallest scale, $2\Delta t$ is selected, and $\delta j$ is the decisive scale number, and the maximum can not exceed 0.5.

The inverse transformation of continuous wavelet transform is as follows:

$$x_n(t) = \frac{\delta j\Delta t^{1/2}}{C_\delta} \sum_{j=0}^{J} \left[ \text{WT} (s_j, t) \right] s_j^{1/2},$$

If the mother wavelet is complex, $x_nA(t)$ represents $x_n(t)$ analytic signal, its real part is $x_n(t)$, and the virtual part is the same as the result of Hilbert transform. $C_\delta$ in equation (10) is the reconstruction coefficient, which can be determined by the following formula:

$$C_\delta = \frac{\delta j\Delta t^{1/2}}{\psi_0(0)} \sum_{j=0}^{J} \left[ \text{WT} (s_j, t) \right] s_j^{1/2},$$

$$W_\delta (s) = \frac{1}{N} \sum_{n=0}^{N} \hat{\psi}^* (s\omega_n).$$

Figure 5 can be found that the data filtered by wavelet transform are smooth in the period of violent fluctuation and the period of stable pressure. This shows that the method of wavelet transform filtering can be used to filter the complex pressure fluctuation phenomenon and get the ideal pressure drop curve.

**Figure 5.** Comparison of wavelet transform filtering effect of shut-in pressure drop data.

4. **Optimization of denoising methods**

From Figure 6, The correction pressure obtained by Savitzky-Golay filter has a certain gap with the measured pressure in the rapid pressure reduction section; FFT is quite different from the measured pressure data. The correction pressure obtained by wavelet transform is in good agreement with the measured pressure, and the relative error is only 0.4%, which meets the accuracy requirements of
injection pressure drop analysis. Therefore, it is suggested to use wavelet transform filtering algorithm to preprocess the pressure drop data of pump stop.

![Figure 6](image)

**Figure 6.** Comparison of three filtering methods and measured data.

### 5. The application of pressure de-noising technology in post pressure effect evaluation

Well X1 is located in team X, group X, X Town, X banner, Inner Mongolia Autonomous Region. It is a development well in the Northeast structural belt of Yishan slope, Ordos Basin.

| Geographical position | Tectonic location                      | Surface elevation(m) | Drilling depth(m) | Artificial bottom hole(m) | Drilled horizon                  |
|-----------------------|---------------------------------------|----------------------|------------------|---------------------------|----------------------------------|
| Inner Mongolia        | Northeast of Yishan slope in          | 1304.52              | 2925             | 2887.90                   | Taiyuan Formation of Carboniferous |
| Autonomous Region     | Ordos Basin                           |                      |                  |                           |                                  |

From Figure 8, wavelet transform filtering can fit the measured data well, and wavelet transform filtering has a good effect in reducing the noise of pumping water hammer oscillation pressure.

![Figure 7](image)

**Figure 7.** Fracturing construction curve of X1 well.

From Figure 8, it can be seen from the figure that the pressure curve filtered by wavelet transform can fit the measured data well. The wavelet transform filter has a good effect in the noise reduction of the water hammer oscillation pressure during the pump stop.

![Figure 8](image)

**Figure 8.** Comparison of wavelet transform filtering effect of pressure drop data in the ninth section
From Figure 9, Pump log fracturing double logarithmic curve pressure derivative curve upturn. The pressure derivative curve of the curve is upward, showing a finite fracture diversion seepage mode with a slope of 0.25. The interpretation skin coefficient is 0.385, the permeability is 1.56 mD, the interpretation fracture length is 29.4m, and the open flow of gas test after fracturing is $2.6 \times 10^4$ m$^3$, indicating that the well hydraulic fracturing construction is relatively successful, which is in good agreement with the analysis results.

![Double logarithmic curve after stopping the fracturing in X1 well.](image)

**Figure 9.** Double logarithmic curve after stopping the fracturing in X1 well.

### 6. Conclusion

The wavelet filtering algorithm has a good denoising effect on the water hammer data of the fracturing construction pump stop data. It is suggested to use this algorithm to preprocess the data in the process of injection pressure drop analysis.

After de-noising the pressure drop data, the double logarithm curve contained in the pressure drop data can be accurately extracted. Injection pressure drop analysis technology can be used in large-scale post pressure effect evaluation.

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