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Data processing method of noise logging based on cubic spline interpolation

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Abstract

Noise logging is a method to determine the natural noise in a well. In the actual production logging process, it is a common situation that the noise data is not continuous with depth, which can be solved by the cubic spline interpolation method. This method is a piecewise interpolation method, which fits with a three-time polynomial in each segment interval, and adds up the polynomials on all intervals to get the interpolation formula. The interpolated data points are a smooth transition with good stability. In this article, the original noise data is interpolated to continuous noise data by cubic spline interpolation method, and then evaluated by noise imaging logging, which presents good results. The cubic-spline interpolation method ensures the internal connection of noise data, and also realizes the fine description and recognition of the characteristics of the output layer. This method will provide a low-cost and effective logging evaluation method for production logging, which has a wide range of applications.

Keywords: noise logging, noise imaging logging, cubic spline interpolation, piecewise interpolation

1 Introduction

Noise logging can measure the natural noise of the wellbore and the area nearby the well. When liquid or gas moves in the wellbore and near the well, sound with a characteristic frequency spectrum can be produced due to friction. Therefore, according to noise logging, the gas production zone and fluid absorption zone can be divided into open hole wells. In cased wells, the location of fluid channelling outside the pipe, the type of fluid, and the flow rate in the pipe and perforation layer can be detected.

In the actual production of oil and gas wells, due to the long-term fracturing, acidification and perforation of the oil and water wells, the casing and tubing of the oil and water wells have been damaged, and the ‘blow-by’

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situation in the oil and water wells increases. The inability to achieve fine water injection seriously affects the production efficiency of oil wells. Noise logging can be used to find leaks and channelling of oil and casing pipes under normal production of oil and water wells. There is no need to set up and run the pipe string, which saves time and effort, and is clean and environmentally friendly.

At present, various oil fields use noise logging in the actual production process. This article uses the data measured by the NTO009-noise logging tool produced by Sondex, and combines the cubic spline interpolation algorithm to process the noise data. After processing, the noise data can well reflect the downhole situation.

2 Principle of noise logging

The fluid in the wellbore and the surrounding medium produces noise of different frequencies due to friction. Generally, low-frequency noise is the result of liquid flowing along tubing and casing; medium-frequency noise generally happens when fluid flows through perforation section blastholes, damaged parts of tubing and casing and crack channels in the cementing; while high-frequency noise comes from the reservoir flow. Through measurement of the noise amplitude and frequency monitored by downhole instruments, combined with the comprehensive analysis of temperature and magnetic positioning curve, the fluid flow position and flow type can be accurately judged, and the production layer can be accurately divided.

Table 1 Types of noise at different frequencies.

No.	Flow type	Frequency range
1	Fluid flow in the well (tubing and casing)	1 kHz
2	Completion tools (perforation, oil and casing perforation)	1–3 kHz
3	Back groove (cement channel, reservoir crack)	3–5 kHz
4	Reservoir flow	10–15 kHz

2.1 Noise data

Noise data is a two-dimensional data with 128 channels of spectral channels, measured by Sondex's NTO009 noise logging tool. The instrument can efficiently detect the fluid inside and outside the cased hole, detect the sound of gas or liquid flowing in the channel or perforation and transmit the detection data to the instrument in real time. The instrument makes use of a very sensitive acoustic sensor, which can measure a wide frequency range in order to effectively detect leaks of various gases, water or oil.

3 Principles of cubic spine interpolation

Due to the complexity of the actual downhole situation, the noise data is discontinuous at the depth point of the well, which means the corresponding noise data is not measured at some depth points, resulting in the inability to explain the formation information. To solve this problem, first the noise data needs to be interpolated, and then filtered, so that unreasonable data is eliminated; the noise data is imaged after filtering is completed, and finally the formation information is reflected according to the imaging effect.

3.1 Cubic spline interpolation function

For a set of discrete data nodes (x_i, y_i) , $i = 1, 2, \dots, N$, $y_i = y(x_i)$, if the function $S(x)$ meets the following three conditions:

- (1) For every x_i , there is $S(x_i) = y_i$;
- (2) S_i is a piecewise function, and for each interval $[x_i, x_{i+1}]$, $S_i(x)$ is a cubic function;

Table 2 Parameters of NTO009 noise logging tool.

NTO009	
Rated work stress	20000PSI (138 MPa)
Rated working temperature	350°F (150 °C)
Dynamic range	72 dB
Frequency range	From 100 to 12,700 Hz
Resolution	16 bit
Number of spectral channels	128 channels
Diameter	1 in. (43 mm)
Length	2.32 ft. (0.71 mm)
Weight	10 lbs (4.53 kg)
Samples length	10 ms
Sampling length	25.6 Hz
Amplifier gain	22.4–67.8 dB

(3) In the entire interval $[x_1, x_N]$, both $S'(x)$ and $S(x)$ are continuous functions. then we can call $S(x)$ the cubic spline interpolation function of function $y(x)$.

3.2 Boundary conditions

For the interval endpoints, there are three types of boundary conditions as follows:

- (1) $S(x_1) = y_1, S(x_N) = y_N$;
- (2) $S'(x_1) = y'_1, S'(x_N) = y'_N$;
- (3) $y_1 = y_N$, which is $S(x_1) = S(x_N)$.

3.3 Algorithm of cubic spline interpolation

The depth value is defined as y , which forms a node (x_i, y_i) with the noise measurement value x . For the boundary conditions, since the depth keeps increasing, only the first or second type of boundary condition can be selected. This article selects the first type of boundary condition and combines the three conditions in Section 2.1. Assuming $M_i = s''(x_i), i = 0, 1, 2, \dots, N$, the following takes place:

$$s''(x) = \frac{x - x_i}{-h_i} M_{i-1} + \frac{x - x_{i-1}}{h_i} M_i$$

$$s(x) = \frac{M_{i-1}}{6h_i} (x_i - x)^3 + \frac{M_i}{6h_i} (x - x_{i-1})^3 + c_1 x + c_2$$

where c_1, c_2 can be calculated by the condition $s(x_i) = y_i, s(x_{i-1}) = y_{i-1}$, and hence:

$$s(x) = \frac{M_{i-1}}{6h_i} (x_i - x)^3 + \frac{M_i}{6h_i} (x - x_{i-1})^3 + \left(\frac{y_{i-1}}{h_i} - \frac{M_{i-1}}{6} h_i\right) (x_i - x) + \left(\frac{y_i}{h_i} - \frac{M_i}{6}\right) (x - x_{i-1})$$

$$x_{i-1} \leq x \leq x_i, i = 1, 2, \dots, N$$

Since $S'(x)$ is continuous, M_i can be calculated as follows:

$$\gamma_i M_{i-1} + 2M_i + \alpha_i M_{i+1} = \beta_i, i = 1, 2, \dots, N-1$$

where $\alpha_i = \frac{h_{i+1}}{h_i + h_{i+1}} \beta_i = \frac{6}{h_i + h_{i+1}} \left(\frac{y_{i+1} - y_i}{h_{i+1}} - \frac{y_i - y_{i-1}}{h_i} \right) \gamma_i = 1 - \alpha_i$, and with the help of the first type of boundary condition, leads to the following:

$$\begin{bmatrix} 2 & \alpha_0 & & & \\ \gamma_1 & 2 & \alpha_1 & & \\ & \gamma_2 & \ddots & \alpha_3 & \\ & & \gamma_3 & \ddots & \ddots \\ & & & \ddots & \ddots & \alpha_{N-2} \\ & & & & \gamma_{N-1} & 2 & \alpha_{N-1} \\ & & & & & \gamma_N & 2 \end{bmatrix} \begin{bmatrix} M_0 \\ M_1 \\ \vdots \\ \vdots \\ \vdots \\ M_{N-1} \\ M_N \end{bmatrix} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \vdots \\ \vdots \\ \beta_{N-1} \\ \beta_N \end{bmatrix}$$

Since the coefficient matrix is strictly dominant on the main diagonal, this matrix equation has a unique solution. There are many ways to solve this tridiagonal matrix equation. This article will use the catch-up method to solve it. The algorithm steps are as follows:

$$1. \text{ Let } A = \begin{bmatrix} 2 & \alpha_0 & & & \\ \gamma_1 & 2 & \alpha_1 & & \\ & \gamma_2 & \ddots & \alpha_3 & \\ & & \gamma_3 & \ddots & \ddots \\ & & & \ddots & \ddots & \alpha_{N-2} \\ & & & & \gamma_{N-1} & 2 & \alpha_{N-1} \\ & & & & & \gamma_N & 2 \end{bmatrix} X = \begin{bmatrix} M_0 \\ M_1 \\ \vdots \\ \vdots \\ \vdots \\ M_{N-1} \\ M_N \end{bmatrix}, B = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \vdots \\ \vdots \\ \beta_{N-1} \\ \beta_N \end{bmatrix}, \text{ then .}$$

Triangulate A to get L , then the original system of equations is equivalent to the following equation:

$$LY = B, UX = Y$$

(2) Solve for $LY = B$, and substitute the calculated value of Y into the equation $UX = Y$. Since the various data are known, X can be calculated.

(3) All the interpolation points can be obtained by continuously integrating the components of X .

4 Noise data processing and interpretation

4.1 Noise data interpolation steps

(1) Mean sampling of noise data at single depth point

The data of well D1 is selected for processing. The measured interval of this well is 5,690.0–5,790.0 m, and the noise data type is point data. There are 29 depth points in total, and each depth point corresponds to a noise data file that changes with time. Therefore, before interpolation, it is necessary to sample the noise data at these 29 depths, and use the sampled noise data to replace the noise characteristics of this depth point.

This article chooses mean sampling, that is, summing the noise data on each channel at each depth point and then taking the average, and finally a data with 1 row and 128 columns can be obtained. Figure 1 shows the curve formed by the noise data before sampling. It can be observed from the image that the curve distribution is relatively clear. Figure 2 is obtained after mean sampling. Comparing the two figures, it can be seen that the curve after sampling can reflect the noise characteristics of the current depth point.

(2) Interpolation processing of noise data at full depth

After step (1), the noise data of 29 depth points is obtained. Because it is not continuous in depth, it is impossible to form a continuous noise image. Therefore, the noise data needs to be interpolated. Before

Fig. 1 Counting rate at 5,774.8 m (before interpolation).

Fig. 2 Counting rate at 5,774.8 m (after interpolation).

interpolation processing, first sample the noise data of each depth point, get the noise data of each depth point after the sampling is completed, and then use each sampled noise data and depth point data as the node (x_i, y_i) ; the depth interpolation step is 0.125 m. Enter the data into the cubic spline interpolation algorithm program for calculation, and the output value is the result of each interpolation. Then five-point average filtering is performed on it, and finally 128 pairs of node data are obtained. As shown in Figure 3, it is the flow chart of the cubic spline interpolation processing program.

The interpolated noise data is imported into MATLAB. Figure 4 shows the noise data of a certain track: the blue circles in the figure are the original noise data, and the red curve is the interpolation result on the depth point (abscissa). It can be seen from the figure that the interpolation curve is smooth everywhere. Because the cubic spline interpolation function has continuous first and second derivatives, there are no discontinuities in the processed noise data, and it has good mathematical properties. In order to detect the accuracy of the interpolation

Fig. 3 Flow chart of the cubic spline interpolation program.

data, the noise data is imaged.

The imaging effect of the noise data depends on the appropriate colour code system, that is, the noise data and the colour code are on one-to-one correspondence. This article takes the maximum and minimum values of the noise data as the endpoints of the colour code interval, and linearly maps the noise data to the RGB colour code space, and finally get the noise imaging picture. Figure 5 is a comparison imaging diagram of linear interpolation and cubic spline interpolation. It can be seen that cubic spline interpolation improves the resolution of noise data while maintaining the linear value structure, and has a better display effect in the local areas.

Fig. 4 Noise interpolation curve.

Fig. 5 Comparison of linear interpolation and spline interpolation.

4.2 Noise data logging interpretation

In order to test whether the cubic spline interpolation is feasible in the logging interpretation process, this paper selects Well D1, combined with the production profile data, and performs imaging logging interpretation on the noise data.

Well D1 is located in the DH area. After consulting the production profile data, the main production zone of this well is from below 5,785.0 m. The water holdup count and fluid density curve of this well both show the flow pattern of oil and water in the wellbore: the oil production is 1.71 m³/d and water production is 20.8 m³/d. The secondary production zone is at 5,755.0–5,777.0 m. The logging curve of this section shows the gradient change in the well temperature curve; the water holdup curve and the fluid density curve also change significantly, and the calculation results of the turbine flow combined with noise show that the section produces oil and water, where the oil production is 8.26 m³/d and water production is 12.49 m³/d.

For the noise data, through research, it is believed that 1–200 Hz corresponds to the fluid flow characteristics of the wellbore area, 300–600 Hz to the oil jacket annulus area (packer sealing conditions can be judged), 600–2,000 Hz to the perforation and transition section, 3,000–8,000 Hz to the formation fluid and 10,000–12,000 to the dense pore fluid. Hence, noise logging interpretation can be analysed from these five frequency intervals.

The noise data is two-dimensional data divided into 128 channels, where the column label is 1–128, its meaning is frequency, and the magnification is 100. The noise data body is the counting rate at the corresponding frequency, which shows the distribution of the counting rate (the distribution of the noise signals).

Figure 6 is the noise production profile of Well DH1, in which the frequency channel is the waveform of cubic spline interpolation data, the amplitude channel is the cumulative count rate curve corresponding to the five frequency intervals and the last channel is the liquid production. Two obvious production layers can be observed intuitively from the figure, which correspond to the main production layer below 5,785.0 m and the secondary production layer in 5,755.0–5,777.0 m, respectively. Besides, there are also a few middle- and high-frequency noise signals near the 5,882 m. Therefore, the noise data processed by cubic spline interpolation not only completely represent the original output layer noise signal, but also monitor the fluid flow in other parts. It can be seen from the imaging channel in Figure 6 that the colour of the rear part of the noise image at 5,882 m is lighter, which is the mid- and high-frequency noise signal. This is because the depth here is just in the transition

region between the main production layer and the measured production layer.

Fig. 6 Production profile result.

5 Conclusion

- (1) In the case that the noise data is not continuous in depth, the noise data at all depths is obtained through the cubic spline interpolation algorithm. Linearly mapped to the RGB colour code space, the noise data is imaged successfully. As a result, the noise imaging measurement of the whole depths is obtained. The well image combined with the production profile data complete the fine description and identification of the production layer of Well D1.
- (2) Based on the noise data of the spot measurement, the noise imaging log images of the whole well section are obtained, which is easy to operate and low in economic cost. At the same time, this method can also be carried out under the condition of normal production of oil and water wells, without the need to re-run the pipe string, saving time and effort, and is clean and environmentally friendly.
- (3) Compared with the linear interpolation method, this method not only realizes the identification of the existing production layers, but also describes the transition areas between the production layers, improves the development efficiency of the production layers and can provide water injection for later wells on a reliable basis.
- (4) Noise logging is an important direction in production logging. Based on noise imaging logging, the reservoir can be further analysed. It will provide a low-cost and effective logging evaluation method for production logging, having extensive value in application.

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