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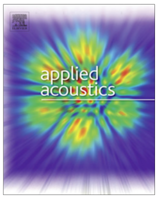

Technical Note

Extracting array acoustic logging signal information by combining fractional Fourier transform and Choi–Williams distribution

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ABSTRACT

Array acoustic logging signals are non-linear. When these signals are processed with traditional methods, such as time-domain methods and frequency-domain methods, they have some drawbacks. In order to improve the situation, this study combines the fractional Fourier transform and Choi–Williams distribution in the signal processing. By this method, the regularities of the distribution of every component wave can be obtained. In the strata with no obvious tectonics, the energy of every component wave showed no significant attenuation. In the strata with fractures, the energy of the Stoneley wave will significantly attenuate and its attenuation will increase with the increasing fracture degree. If the fracture is vertical or high angle to the horizontal, the energy of the longitudinal wave will attenuate some and the energy of the shear wave will change little. If the fracture is parallel or low angle to the horizontal, the energy of the longitudinal wave will attenuate a little and the energy of the shear wave will attenuate obviously. Besides, by comparing the time of components that do not attenuate completely, different lithology can be distinguished.

1. Introduction

Acoustic logging is one of the main methods of geophysical logging, which is mainly used to study geological profile by acoustic properties of rocks. Acoustic logging was created in twentieth century 50s. It only measured the arrival time or amplitude of the first wave that spreads along the wall (longitude wave). In order to expand the application of acoustic logging, array acoustic logging was invented. Array acoustic logging has multiple receivers. It obtains signals through different combinations of these receivers after the transmitter sends acoustic signals. Compared to the early acoustic logging, array acoustic logging explores more widely, and can receive various waves. At present, in the world, the most famous logging instruments include DSI (Schlumberger), MAC and XMAC (Atlas) and WaveSonic (Halliburton). The measurement principle of logging instruments can be seen in Fig. 1.

The signals received by the instrument contain abundant information, but they need to be processed and analyzed. At now, there are two kinds of traditional methods [1,2]: time-domain methods and frequency-domain methods. But the time-domain methods ignore the signal dispersion. So if the dispersion is serious, these methods are not reliable. While the drawbacks of frequency-domain methods are that these methods cannot offer the time information for a component at a certain frequency, and the amplitude of components of various frequencies at a certain time.

In order to solve the above problems, time–frequency analysis methods could be introduced. The advantage of these methods is that time, frequency and amplitude are tied together. To be more precise, the amplitude of a signal can be distributed in the time–frequency coordinate system. Time–frequency analysis methods are often divided into two categories: linear methods and non-linear methods. The linear methods mainly include Gabor transform [3], wavelet transform [4], Hilbert–Huang transform [5] and fractional Fourier transform [6], and the nonlinear methods mainly include Cohen class bilinear time–frequency distribution [7] and Affine class bilinear time–frequency distribution [8].

In acoustic signal processing, time–frequency analysis methods have been applied [9,10]. However, in general, there are two problems. For the majority of linear methods, the selection of the window function or wavelet bases is crucial, but it may also be challenging. For nonlinear methods, cross-term problems are inevitable. In addition, if the time or frequency of every component of a complex signal is similar, these components will interfere with each other in the time–frequency distribution figures. Distinguishing these components is almost impossible, making the signal analysis hugely difficult. Therefore, after studying the relative mathematical theories of the fractional Fourier transform and the

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Choi–Williams distribution, we decided to combine the two methods to process and analyze the array acoustic logging signals. The fractional Fourier transform was first suggested by Condon [6] in 1937. In the following decades, Namias [11], McBride and Kerr [12], Lohmann [13], Almeida [14] and Shih [15] refined the method. It has a unique characteristic. When the order of the fractional Fourier transform increases, it will rotate the signal, which will help to separate the components of a complex signal. On the other hand, the Choi–Williams distribution, which was proposed by Choi and Williams [16] in 1989, is one of the Cohen class bilinear time–frequency distributions. Unlike other Cohen class distributions, the Choi–Williams distribution has weakly interfering cross-terms. For array acoustic logging data of a certain depth point, we will first apply the fractional Fourier transform with different orders, and then develop the Choi–Williams distribution of the transformed signal. Through these figures, we can summarize the change law of the Choi–Williams distribution with the changing order of the fractional Fourier transform and the characteristics of array acoustic logging signal components. Using these figures, we can identify strata with different fracture degree and different lithology. This method take advantage of the rotation of the fractional Fourier transform and the weakly interfering cross-terms of the Choi–Williams distribution, which is more superior than the single time–frequency analysis method.

2. Full-waveform of array acoustic logging

The components of an array acoustic logging signal are very complex, according to the arriving time to the receiver these components can be described as longitudinal wave, shear wave, Stoneley wave, etc.

The longitudinal wave is a body wave that propagates by sliding along the wall of the well. The wave surface is conical, the amplitude is low, and propagation velocity is fast. By choosing the appropriate spacing of logging instruments, the longitudinal wave is the head of the full waveform. The longitudinal wave had certain significance in fracture studies. While entering a stratum with a fracture, the energy of it will attenuated. If the fracture is vertical or high angle to the horizontal (dip angle > 70°), the energy of it will be severe attenuation [17].

The shear wave is also a body wave that propagates by sliding along the wall of the well. The wave surface is conical, the wavelength is short, and the amplitude is higher than that of the longitudinal wave. When the shear wave velocity is faster than the fluid velocity in the well, this wave will be received by the logging apparatus. By choosing the appropriate spacing, the shear wave is the second wave of the full waveform. The shear wave is important for fracture studying. It is only sensitive to the fracture that is parallel or low angle to the horizontal (dip angle < 35°). While entering this stratum, its energy will attenuates obviously [17].

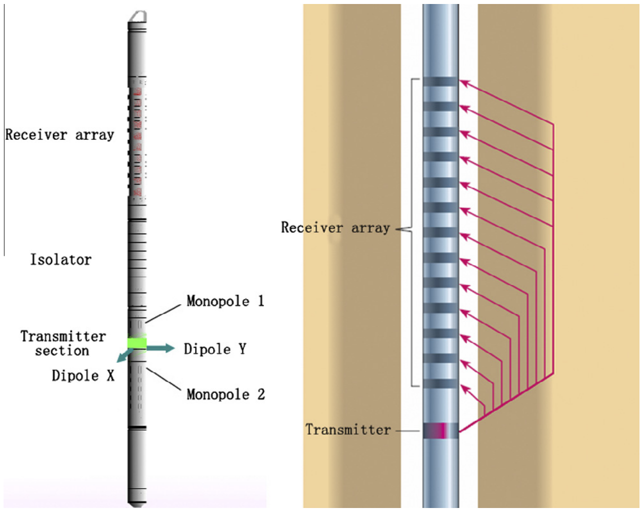

Fig. 1. XMAC-II and its measurement principle.

The Stoneley wave is a surface wave. It is distributed over a wide range of frequencies, and its energy is concentrated in low frequencies. The propagation velocity is slower than both that of the longitudinal wave and the shear wave; thus, it appears later in the full waveform. The Stoneley wave is very sensitive to the strata permeability. When the Stoneley wave enters a permeable stratum, the fluid significantly vibrates compared to the solids in the well, and the wave diffuses in these strata. Viscous diffusion causes the energy of the Stoneley wave to substantially attenuate.

3. Time–frequency characteristics of different strata

In this study, all data are obtained from the Chinese Continental Scientific Drilling (CCSD), which employs the XMAC-II cross-dipole acoustic logging instrument. The method presented in this study combines the fractional Fourier transform and Choi–Williams distribution. Roughly speaking, we process an array acoustic logging signal by the fractional Fourier transform, and treat the result as a new signal. Then, we determine the Choi–Williams distribution of the new signal to obtain the final result. Because the fractional Fourier transform can be used as a rotation operator, the Choi–Williams distribution figures constructed after the fractional Fourier transform will be rotated compared to the Choi–Williams distribution figures constructed without the fractional Fourier transform. As the fractional Fourier transform order increases, the rotation angle increases. However, the fractional Fourier transform does not perform a simple rotation of the logging signal components. In the process of the rotation, there are additional changes. It will be discussed in the following.

Fig. 2 contains a series of Choi–Williams distribution figures, which are produced with a certain depth of data, and by choosing different orders of the fractional Fourier transform (from order $\alpha = 0$ to order $\alpha = 0.45$ in intervals of 0.15). In these figures, the horizontal axis represents the arrival time (in seconds) and the vertical axis represents the frequency (in kilohertz). The contour lines represent the amplitude (no unit), and the characteristics of the signal amplitude can be used to reflect the energy distribution.

Fig. 2(a) with order $\alpha = 0$ is equivalent to the Choi–Williams distribution of the logging signal without first performing the fractional Fourier transform. As shown in Fig. 2(a), the Choi–Williams distribution is symmetric. Here, we are only interested in the lower part of the distribution ($f < 13$ kHz). Between 1.4×10^{-3} s and 3×10^{-3} s, we find a dense, easily distinguishable area of contour lines. This is the Stoneley wave because the velocity of the Stoneley wave is the slowest in the waveform. Between 0.5×10^{-3} s and 1.2×10^{-3} s, the wave components are more complicated. The arrival time and the frequency of the longitudinal wave and the shear wave are similar. Consequently, these waves will interfere with each other, making them impossible to distinguish, and introducing many challenges in the array acoustic logging signal analysis. Therefore, we can use Fig. 2(a) to study the distribution characteristics of the Stoneley wave only.

From Fig. 2(a)–2(d), as the order increases, the symmetrical features of the Choi–Williams distribution in Fig. 2(a) rotate. The upper part of the distribution gradually rotates counter-clockwise out of the figure, while the lower part of the distribution gradually rotates toward the right-hand side of the figure. In this process, the mutually interfering waves will gradually separate, and the Stoneley wave will gradually disappear. In Fig. 2(d) with order $\alpha = 0.45$,