Feature Extraction of Down-hole Drilling-plug Impact Signal Based on Empirical Mode Decomposition

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ABSTRACT—For analyzing the non-stationary drilling-plug impact signal under the complicated drilling environment, use of conventional discrete Fourier Transform (DFT) has been known to be less efficient. To extract useful information contained in the drilling-plug impact signal, a new extraction method based on empirical mode decomposition (EMD) is presented. In the signal processing, EMD is used to decompose the original drilling-plug impact signal into the intrinsic mode functions (IMFs). By analyzing kurtosis and energy spectrum of the IMFs, the first three IMFs are found that contain the characteristic of the drilling-plug, and the specific frequency band of the drilling-plug impact signal is determined after power spectrum analyzing. The reconstruction drilling-plug impact signal after band-pass filter can clearly show the detailed process of the drilling-plug such as drilling the rubber plug, drilling the float collars and drilling the formation.

1. INTRODUCTION
The drilling plug operation is widely used in oilfields to drill out the solidified cement plugs or bridge plugs that left in the well casing after cementing job. At present, there are three ways to perform drilling
plug operations which are using the positive displacement motor, using the power swivel and using the rotary table to drill cement plug [1]. In the process of drilling plug operation, the petroleum engineer mainly rely on the drilling parameters such as the WOB (weight on bit), the drilling rate, the drilling fluid velocity in annular, etc. to analysis and get the drill bit working condition [2, 3]. It is easy to damage the down-hole drilling tools due to improper operation in the complicated down-hole condition, which not only affects the operation progress, but also increases the operating cost. The industry has an increasingly need for an effective way to accurately evaluate the down-hole drilling plug condition.

The down-hole drilling plug monitoring system is developed by using drill bit impact signal to detect the drill bit working condition in real-time, and give warning or alarm when the down-hole condition become complicated. Because the drilling-plug impact signal is non-linear and non-stationary, conventional discrete Fourier Transform (DFT) based on the assumption that the signal is stationary and liner can result in false information [4, 5, 6, 7]. In addition, there are strong noises such as pump trucks, generators, engines, personnel and vehicles moving at the well site. How to extract characteristic from the collected data is a tough problem. Considering the actual situation of the drilling plug, in this paper we take the empirical mode decomposition method to extract useful information, and focus on the local characteristics of the signal to improve the interpretation accuracy.

2. FEATURE EXTRACTION PROCESS

2.1. Empirical mode decomposition

Empirical Mode Decomposition (EMD) is a time-frequency analysis method for processing nonlinear and non-stationary signals. It is an important part of the Hilbert-Huang transform proposed by Dr. Norden E. Huang, a Chinese American NASA scientist in 1998 [8]. The input signal can be adaptively decomposed into multiple Intrinsic Modulus Functions (IMFs) according to its own characteristics, without any prior information. The IMFs meet the following two conditions:

1. In the entire data set, the number of extreme points and the number of zero-crossing points must be equal or at most one difference;
2. At any time, the average value of the envelope defined by the local maximum and the envelope defined by the local minimum must be zero. Namely the signal is locally symmetric on the time axis.

First, identify all local maxima from the given signal, and then use cubic spline curve as the upper envelope. Second, repeat the first step for the local minimum to generate a lower envelope. The upper and lower envelopes should cover the entire signal between them. Third, specify their average value as m(t), and the difference between the signals x(t) and m(t) as the first component h(t). In order to obtain the IMF that meets the requirements, h(t) is used as the signal x(t), and the screening process is repeated until h(t) becomes the real IMF, order C1(t)=h(t). C1 (t) is removed from the remaining signals by R1(t)=x(t)-C1(t). By treating R1 (t) as a new signal and repeating the same sifting process as described above, we can get the second IMF C2(t). Similarly, we can get a series of IMFs C1(t), C2(t)...Cn(t) and the final remaining r_n. Summarize all the IMFs and the remaining signals, we should be able to rebuild the original signal x(t) by

\[ x(t) = \sum_{i=1}^{n} C_i(t) + r_n(t) \]  

2.2. Signal characteristic extraction.

Kurtosis is chosen as the characteristic parameter for evaluating bit vibration signals, because it is more sensitive to impact signals. Kurtosis (K) is a numerical statistical method that reflects the distribution characteristics of vibration signals [9]. It is the fourth-order standardized central moment:

\[ K = \frac{\int_{-\infty}^{\infty} [x(t) - \bar{x}]^4 p(x) dx}{\sigma^4} \]  

(2)
Where $x(t)$ represents instantaneous amplitude, $\bar{x}$ represents mean amplitude, $p(x)$ represents probability density, $\sigma$ represents standard deviation.

For a given set of discrete signal, the kurtosis coefficient is:

$$K = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{x_i - \bar{x}}{\sigma_i} \right)^4$$  \hspace{1cm} (3)

Where $i$ represents discrete point position in signal, $x_i$ represents signal amplitude, $\bar{x}$ represents mean amplitude, $N$ represents sampling length, $\sigma$ represents the standard deviation.

$$K_i = \frac{K_i}{\sum K_i}$$  \hspace{1cm} (4)

Where $i$ represents IMF label, $m$ represents IMF number of IMFs.

The kurtosis analysis is aimed at the change of the signal in the time domain, and it is necessary to obtain more information about the vibration and shock characteristics of the drill bit in the frequency domain. In this paper, the power spectrum analysis of the internal model filter with characteristic information is carried out to effectively extract the detailed characteristics of the bit signal [10]. The signal processing flow is as shown in Fig. 1.

Fig.1 Drill plug signal processing

3. FIELD TEST DATA ANALYSIS

The field test (Fig. 2) was performed on Well X (casing size: 9 5/8, top of cement: to the ground, float collar position: 1390m) in a certain oil field of East China. The accelerometers are installed at the surface of the technical casing using the drilling-plug Monitoring system to collect the signal. The sampling frequency is 4000Hz, and the data collection interface shown in Fig. 3 (selected part while no drilling plug), Fig. 4 (Spectrum analysis of no drilling plug signal), the playback data shown in Fig. 5 (selected part while no drilling plug).

In Fig. 3, when the equipment on the well cite stop working (stop drilling), the signal amplitude is very low in $\pm 0.01 \text{mm/s}^2$ which stand for the natural noise, the other channel changes the same indicating that the sensors have a good consistency. In Fig.4, the Spectrum of no drilling plug signal shows that the frequency of the natural noise is 0-200Hz, which should be filtered. Take the drilling-plug signal of well
X in the time period from 1:12:16 to 1:12:20, reconstruct the signal after the band-pass 200-4000Hz filtration (Fig. 5).

Fig.2 Sketch of sensors installation

Fig.3 Time domain signal while no drilling plug

Fig.4 Spectrum analysis of no drilling plug signal
According to signal processing flow, do signal feature extraction of the Playback time domain signal while drilling plug in Fig. 5. First make EMD decomposition, get IMFs and residual component re (Fig. 6), and then do the normalized kurtosis and energy distribution (Fig. 7).

In Fig. 6, EMD decomposes the signal of drilling well and existing well into several IMFs and different IMFs contain different time scales, which can make the signal characteristics at different resolutions. The frequency of each component (IMF1-IMF11) is from high to low. IMF1-IMF4 shows a higher frequency and amplitude. Residual component re is monotone trend item.

In Fig. 7, the energy of IMF1-IMF3 hold majority of the original signal energy, over 99%, and the kurtosis variation indicates that the impact characteristics of drill bit concentrated in the first few IMFs, especially in IMF1, IMF2, IMF3. As IMF6-IMF12, the seven components change slowly in time.
Take the first three IMFs to do the power spectrum analysis (Fig. 8). The power spectrum shows that the drilling plug signal has large frequency distribution, IMF1 of the drilling plug signal is high frequency, wideband and has no coherence, IMF1 and IMF2 have the same 800-1000Hz frequency band and much higher amplitude than the other IMFs, which shows the drilling plug impact characteristic, IMF3 has 200-400Hz frequency band and much lower amplitude. After processing a large number of measured data, the results of the EMD and power spectral analysis are the same.

Take the drilling-plug signal of well X in the time period from 00:45:00 to 3:30:20 which is the whole drilling-plug operation, reconstruct the signal with IMF1, IMF2 and do the band-pass 800-1000Hz filtration (Fig. 9). In Fig. 9, the whole drilling-plug operation can be clearly divided into three parts, I is drilling the rubber plug process, II is drilling the float collars process and III is drilling the formation process according to the maximum amplitude of the time domain signal, which can be used to accurately evaluate the down-hole drilling plug condition.
4. CONCLUSIONS

The characteristic extraction method based on empirical mode decomposition was proposed to process the drilling-plug impact signal for down-hole drilling plug monitoring, and proved effective by the field test data analysis. By the field test data analysis, we draw the following conclusions:

1. Using band-pass (200-4000Hz) filtration can effectively reduce ground noise interference and increase the accuracy of drilling-plug impact signal.

2. The drilling-plug impact signal consists of three frequency bands, 200-400Hz, 800-1000Hz, 1600-1800Hz, and 800-1000Hz frequency band particularly reflects the drilling plug impact characteristic.

3. The reconstruct signal with IMF1, IMF2 in 800-1000Hz frequency band can clearly shows the detailed process of the drilling-plug such as drilling the rubber plug, drilling the float collars and drilling the formation.

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REFERENCES

[1] Yongquan Hu, Jin Zhao, Jinzhou Zhao, Chaoneng Zhao, Qiang Wang, Xing Zhao, and Yan Zhang. 2019. Coiled Tubing Friction Reduction of Plug Milling in Long Horizontal Well with Vibratory Tool. Journal of Petroleum Science and Engineering, 452-65. DOI=https://doi.org/10.1016/j.petrol.2019.02.042.

[2] Daniel A D, Dennis L D. 2000. Bridge-plug millout with coiled tubing case histories. SPE 60725. DOI= https://doi.org/10.2118/60725-MS.

[3] C.M.Cromer, I.Aviles, N.Li.Composite. 2014. Is multi-plug milling that fast?. SPE168301. DOI= https://doi.org/10.2118/168301-MS.

[4] Linfei Wang, Huaishan Liu, Siyou Tong, Yanxin Yin, Lei Xing, Zhihui Zou, Xiugang Xu. 2015. Retrieving Drill Bit Seismic Signals Using Surface Seismometers. Journal of Earth Science, 67-576. DOI= http://dx.doi.org/10.1007/s12583-015-0568-1.

[5] XuSong Xu, ZhiYing Sun.2013. Multi-Sensor Data Fusioning of Monitoring Deep-Hole Drill Bit. Advanced Materials Research, 1165-1169. DOI= https://doi.org/10.4028/www.scientific.net/AMR.718-720.1165.

[6] Qu, Y.P., Wang, C.Y., Zheng, L.J., Song, Y.X., 2012. Wavelet Transform Denoise of PCB Drilling Force Signal. AMR 500, 26–31. DOI= https://doi.org/10.4028/www.scientific.net/amr.500.26.

[7] Poletto, Flavio. 2000. Drill-bit signal separation for RVSP using statistical independence. Geophysics, 1654-1659. DOI=http://dx.doi.org/10.1190/1.1444853.

[8] N.E. Huang, Z. Shen, S.R. Long. 1998. The Empirical Mode Decomposition and Hilbert Spectrum for Non-linear and Non-stationary Time Series Analysis. Proceedings of the Royal Society: Mathematical and Physical Sciences, vol.454, PP. 903-995.

[9] Su, W. S., Wang, F. T., Zhang, Z. X., Guo, Z. G., & Li, H. K. 2010. Application of EMD denoising
and spectral kurtosis in early fault diagnosis of rolling element bearings. Journal of Vibration and Shock, 29(3), 18–21.

[10] Jiedi Sun, Jiangtao Wen, Shijiu Jin. 2008. Study on Target Localization Method for Pipeline Monitoring System Based on HHT, Chinese Journal of Scientific Instrument, vol. 29(12):2492-2496. DOI= http://dx.doi.org/10.19650/j.cnki.cjsi.2008.12.006.