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Abstract

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Keywords: data acquisition; stick slip; power spectral density; wavelet transform

井下数据获取及粘滑特征分析

黄升 [1]，张涛 [2]，黄崇君 [3]，李玉梅 [2]，邓虎 [3]，张霞 [1]

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摘要：在石油钻井过程中，钻柱振动对钻头和钻柱有害，甚至导致钻具失效。研究近钻头振动数据规律可以减少非生产时间(NPT)，提高钻井效率。用功率谱密度和小波变换来分析振动信号，与正常钻进情况进行比较，找出粘滑特征。结果表明，当发生粘滑时，*横向振动的平均值波动很大，表明粘滑振动主要基于扭转振动*。从功率谱密度分析的角度来看，*单位频率的能量大于正常钻进时的状态*。此外，在*粘滑时频域中存在与正常钻井不同的明显峰值*。可帮助司钻优化钻井参数，提高钻井速度(ROP)并降低钻井成本。

关键词：数据获取；粘滑；功率谱密度；小波变换
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Introduction

During oil drilling process, stick slip vibration is the main cause of drill string fatigue, drill string wear, drill failure and wellbore expansion. Preventing stick-slip of the drill string early can avoid drilling accidents and improve drilling efficiency.

Vibration is inevitable. In many cases, vibration is harmful to drill string. And severe drill string vibration causes low ROP, lengthy drilling time, spoilt bit,

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damage to motor steerable, even damage MWD (Measurement While Drilling) /LWD (Logging While Drilling) tools causing lost data, increasing fatigue of drill string[1]. Gabriel P. G. Sotomayor et al.[2] study how to reduce drill string vibration so as to reduce drilling cost. R.V. Westermark et al.[3] stimulate downhole vibration data to enhance oil recovery.

Numerous studies, predominantly focus on stick slip vibration. Stick slip is a self-sustaining cyclical form of torsional vibration characterized by stop and rapid acceleration of the BHA (bottom hole assembly). The result of this drilling dysfunction is reduced ROP, excessive bit wear, tool failure, drill string fatigue, and even failure resulting in added costs and non-productive time (NPT) to the well[4]. L.W. Ledgerwood III and M.J. Fear[5-6] reveal that stick slip is a primary cause of PDC bit damage. E.W. Robnett et al. [7] analyze stick slip with PDC bit and Tricone bit characterizes, and find that downhole RPM data is useful in define the stick slip. Thomas Richard et al.[8] analyze stick slip vibrations of PDC bits, and introduce the coupling between vertical and torsional vibrations of the drill assembly as an alternative cause to stick slip vibrations. Luciano P.P. de Moraes et al.[9] analyze bit-bounce, stick-slip, whirl, and the interaction among them under different drill-string length and various rotary table speed. Ulf Jakob F. Aarsnes et al.[10] design a feedback controller, which can be added to the industry easily, without disturbing their closed-loop behavior and avoiding torsional stick slip oscillations at the start-up of a drilling operation. G. Heisig[11] make use of MWD provide real-time feedback about the drilling process to the driller, and identify stick slip, BHA whirl, bit bounce via weight on bit and RPM. G.W. Halsey et al.[12] present a novel idea called “Torque Feedback” to control the rotary speed by change drilling string torque, and this method can effectively reduce the reflection of torsional waves and absorb vibration energy. Zifeng Li et al.[13-15] build mathematical models to analyze longitudinal vibration, torsional vibration and lateral vibration of the drill string. Etaje Darlington Christian[1] and Sean Xianping Wu[16] optimize weight-on-bit (WOB) and revolutions per minute (RPM) to decouple stick slip and whirl to increase overall drilling performance. The vibration data includes the vibration caused by the drill string, the working condition of the drill bit, the vibration excited by the interaction between drill bit and formation, the collision between drill string and well wall, and stuck-release[17-18]. Wenqing Qiu[19] make use of Fourier transform to analyze stick slip and bit bouncing vibration data, when stick slip occurs, there is high amplitude of low frequency torsional vibration; while bit bounce occurs, high amplitude of low frequency of axial torsional vibration. There are two ways to reduce stick slip: one is to increase rotary speed and reduce weight on bit, another is to decrease rotary speed and increase weight on bit[20].

According to researches, it is possible to mitigate stick slip vibration if we can accurately identify. Traditional drill string vibration analysis methods are based on physics-based model and mathematical model. This paper, from the perspective of signal processing, analyzes the normal drilling and stick-slip signals to find out the characteristics of the stick-slip vibration signal. And it provides a new direction to analyze stick slip vibration, even frequency domain and wavelet transform characteristics of stick-slip still require further proof. Once it is proven, it will help the driller adjust drilling parameters in real-time, which can reduce drilling cost and improve drilling performance.

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1 Data Acquisition and Vibration Forms

Vibration data is collected by downhole measurement short section. At present, the tool cannot transmit data to the surface in real-time, and measurement data only can be analyzed after drilling completed.

1.1 Data Acquisition

The tool is developed by China University of Petroleum, equipped with strain gauge bridge to measure weight, torque, and bent in two orthogonal directions. The tool is designed for 150°C temperature, which contains various dynamics sensors that measure eight parameters, as internal bore pressure, external pressure, weight-on-bit, torque, temperature and three-axis acceleration. The sensor of three-axis accelerometer is mounted on the tool, which is 58 mm from the center of the drill string, as shown in Fig. 1.

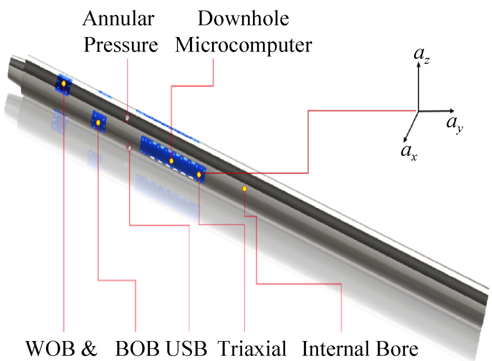


Fig. 1 Mounting position of vibration sensor

Where a_x and a_y represent the acceleration along the radial direction of drill string and the tangential direction of drill string, a_z indicates axial vibration. According to the installation method of accelerometer, the relationship between acceleration of drill string center and three-axis acceleration sensor is shown in following equations:

$$a_x = a_{cx} + r\omega^2 \tag{1}$$

$$a_y = a_{cy} + r(\mathrm{d}\omega/\mathrm{d}t) \tag{2}$$

$$a_z = a_{cz} \tag{3}$$

where ω is downhole speed of drill string, rad/s; a_{cx} and a_{cy} are two orthogonal components of lateral vibration of drill string center, m/s^2; a_{cz} is the axial acceleration of drill string center; t is time, s.

1.2 Forms of Vibration

Drill-string vibration is a complicate condition that can be divided into three different vibration models: axial, torsional and lateral.

1.2.1 Axial vibration

Axial vibration results from uneven of the bottom hole, inconstant contact and friction at the borehole and rock formation interfaces, it can be calculated by Equation (3). Bit bouncing is caused by strong axial vibrations in such a way that the bit loses contact with the rock formation at the bottom of the hole. This type of vibration can cause bit bounce (up and down movement of the bit and string along its central axial) which destroys bits, damages BHA, slows down the rate of penetration[21]. When bit bouncing occurs, the amplitude of axial vibration is large enough, even can be observed on the surface.

1.2.2 Torsional vibration

Torsional vibration is caused by the varying rotational speed generated when the drill bit breaks the rock intermittently. This type of vibration makes the rotation of the bit irregularly and may causes bit wear and pipe connections broken. During drilling processing, the torsional vibration is main vibration of break rock, stick slip and penetrate into new formation. The calculation formula of the torsional vibration (a_{tor}) is as shown in Equation (4).

$$a_{tor} = \bar{a}_x - \bar{a}_y \tag{4}$$

where $\bar{a}_x$ is mean value of x-axis vibration, $\bar{a}_y$ is mean value of y-axis vibration.

1.2.3 Lateral vibration

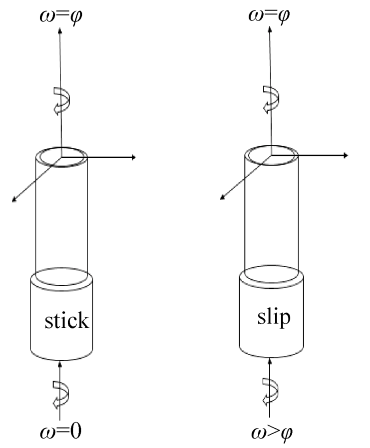
When the bit or the stabilizer rotates with a center of rotation that is not coincident with the center of the well, which is called lateral vibration, and it will cause hole enlargement. During the drilling process, the axial alternating force and displacement of the drill bit are the main factors of lateral vibration[10]. And lateral vibration (a_{lat}) is computed by Equation (5).

$$a_{\text{lat}} \approx \sqrt{{a_x}^2 + {a_y}^2} \tag{5}$$

1.3 Stick Slip Characteristics

During normal drilling process, drill-string vibration is represented by a periodic behavior with amplitudes no more than 10g (g=9.8 m/s^2). Researches show that, when drilling normally, the three-axis vibrations signals are stable in time domain, and the range of vibration amplitude is between 0~10 g.

Stick slip vibrations are based on torsional vibrations where the bit rotates through periodically two phases[22]: sticking (the bit stops rotating, Fig. 2(a)) and slipping phases (the bit is released from sticking phase with angular velocity higher than nominal velocity, Fig. 2(b))[7]. φ represents the surface rotary speed, ω represents actual downhole bit speed. Therefore, stick-slip is mainly based on torsional vibration.



(a) Stick phase (b) Slip phase

Fig. 2 Stick-slip motion diagram

2 Signal Processing Methods

There are three traditional methods processing vibration signal: time domain methods, frequency domain methods and wavelet transform methods.

2.1 Time Domain Methods

Time domain analysis is the most common method of signal process. For example, the variance can reflect the degree of fluctuation of signal. The larger the variance, the larger the signal fluctuation and the worse the stability.

2.2 Frequency Domain Methods

The power spectral density reflects the amount of energy at the unit frequency of the signal. According to Winner-Khintchine formula, R(τ), the autocorrelation function and the power spectral density are mutually Fourier transform(FT) pairs.

$$\mathrm{P}(\omega) = \int_{-\infty}^{+\infty} \mathrm{R}(\tau) e^{-j\omega\tau} \mathrm{d}\tau \tag{6}$$

where R(τ) is autocorrelation function,

$$\mathrm{R}(\tau) = E[x(\mathrm{t})\, \mathrm{x} \times (\mathrm{t} - \tau)] \tag{7}$$

Since the signal x[n] is discrete, the Discrete Winner-Khintchine formula is

$$\mathrm{P}(\omega) = \sum_{k=-\infty}^{k=+\infty} r[\mathrm{k}] \mathrm{e}^{-\mathrm{jk}\omega} \tag{8}$$

$$r[\mathrm{k}] = \sum_{k=-\infty}^{+\infty} x[\mathrm{n}] \mathrm{x}^*[\mathrm{n} - \mathrm{k}] \tag{9}$$

where r[k] is autocorrelation function.

2.3 Time-Frenquency Domain Methods

The mainstream time-frequency domain analysis methods are Wavelet Transform (WT) and Short-Time Fourier Transform (STFT). Wavelet Transform[23] has been applied widely. It breaks through the limitation of Fourier Transform in time domain. And it can analyze feature points both in time domain and frequency domain. Using gradually fine sampling step of time or frequency domain, wavelet can focus on any detail of the

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signal. Nowadays, wavelet transform is used widely in signal processing. It is a more powerful tool than traditional Fourier Transform. The wavelet transform methods have good performance both in the time and frequency domain, which can show certain adaptive ability to the data[24] and reflects the characteristics of signal more clearly than Fourier transform (FT).

$$W_f(a,b)=\int_R f(t)\overline{\varphi}_{ab}(t)\,dt \quad (10)$$

$$\varphi_{ab}(t)=|a|^{\frac{1}{2}}\varphi_{ab}(t)\,dt \quad (11)$$

where φ_{ab} is a two-parameter band-pass filter, a is called the scale parameter, which changes the bandwidth of the filter, and determines the frequency information in the wavelet transform; b is the position parameter, determines the spatial or time domain information in the transformation results. The discrete form of the wavelet transform is shown in Equations (12) and (13).

$$\varphi_{j,k}(t)=2^{\frac{j}{2}}\varphi(2^j t-k) \quad (12)$$

$$W_f(j,k)=(f(t),\varphi_{j,k}(t)) \quad (13)$$

The essence of the Fourier transform is to decompose the signal into a combination of sine and cosine signals. From Equation (10), the essence of Wavelet Transform is to decompose the signal into different scales. In this paper, we use “Morlet Wavelet” to analyze vibration signals. The scale of Morlet Wavelet is 256, which is the N power of 2.

3 Numerical Experiment

The tools were applied in Jidong Oilfield of China, and the instrument was powered on at 3:33 on 2017-10-29, shown as Fig. 3. Sever stick slip occurs at 10:56 on 2017-10-30, and data were analyzed with following drill assembly:215.9 mmMD9431 drill bit×0.33 m+430×410joint×1.11 m+411×410float valve×0.50 m+172 mm drill collar×3 m+208 mm centralizer×1.532 m+ near drill bit measurement short section×3.255 m+165 mm non-magnetic drill collar ×17.135 m+411×4A10× 1.1 m+165 mm drill collar×27.575 m+4A11×410× 1.13 m+127 mm weighted drill pipe×197.595 m+ 127 mm drill pipe. During the experiment, sampling frequency of the circuit board is 100 Hz.

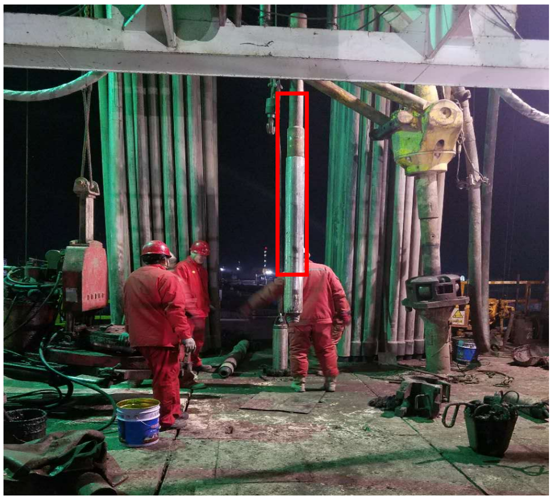

Fig. 3 Field experiment

Downhole RPM simulation is shown as Fig. 4. From the picture, stick slip occurred, because when the bit periodically stops (stick), downhole RPM reaches zero. And when bit rotates again (slip), downhole speeds accelerate two times the surface RPM. Next step makes use of different methods to analyze those data to find out stick slip vibration signal characteristics.

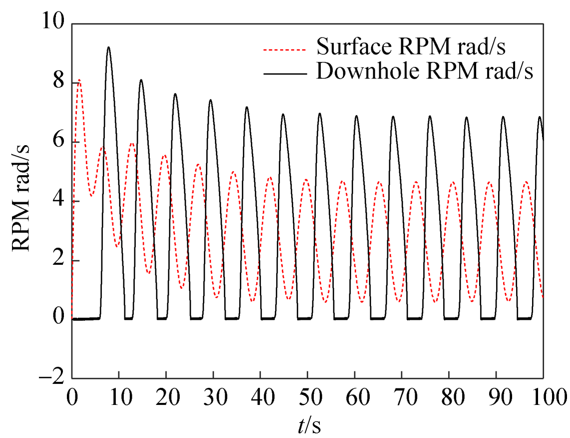

Fig. 4 Surface RPM and downhole RPM

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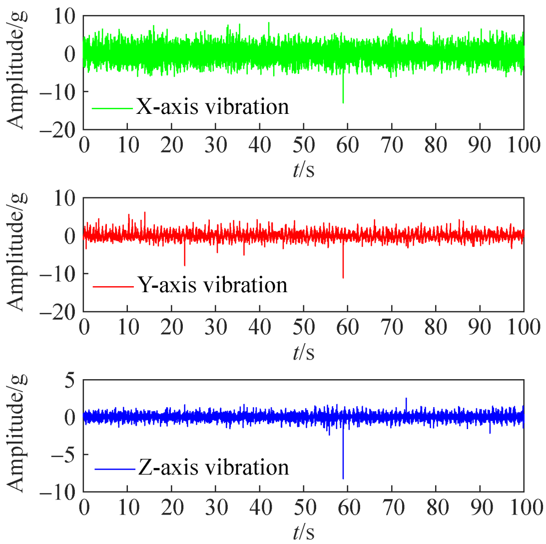
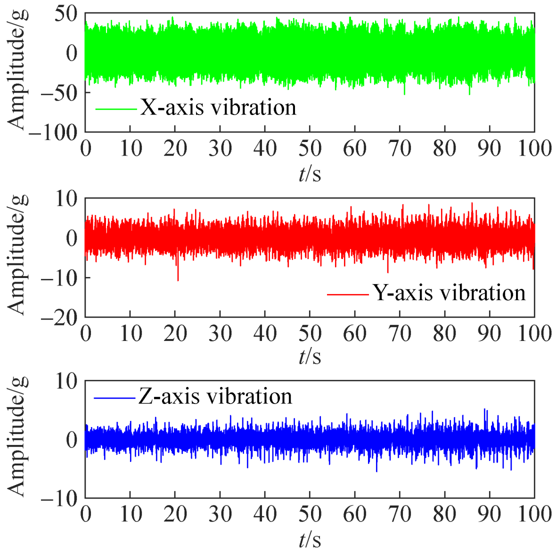
3.1 Time domain analysis

Three dimensional acceleration are analyzed based on time domain. While normal drilling, the three axial accelerations is shown in Fig. 5(a). The range of three axial accelerations is 0~10 g. When stick slip occurs, the amplitude of X and Y-axes become large, which is shown in Fig. 5(b). The maximum amplitude of X-axis vibration is 50 g while normal drilling is 10 g. Meanwhile, there is no significant change in Y and Z-axes vibrations.



(a) Normal drilling



(b) Stick slip

Fig. 5　Time domain vibration diagram

For stick slip data, the mean value, variance value and mean square error value are calculated every 100 points, as shown in Fig. 6. From the picture, the mean value, variance value and mean square error value of X-axis vibration are larger than Y and Z-axes. Especially the variance value and the mean square error value of X-axis vibration, are almost 100 times of Y-axis. Stick slip will have a process of release and stick phase, causing two lateral vibrations to fluctuate periodically. The mean value between X and Y-axes vibration differs large, so torsional vibration is severely. This indicates that stick slip vibration is mainly based on torsional vibration.

3.2 Frequency domain analysis

Vibration data can be retrieved after power spectral density via data processing software. The X-axis power spectral density of normal drilling and stick-slip is shown in Fig. 7. There is a distinct peak at 24 Hz of X-axis power spectral density in stick-slip vibration, which means energy is concentrated on this dominant frequency.

The stick slip X-axis vibration power spectral density is relatively large, and overall deviated from horizontal coordinate. From the picture, it is easily to distinguish normal drilling and stick slip by power spectral density. There is a dominant frequency of 24 Hz (Fig. 8(b)) in Y-axis power spectral density, which is smaller than X-axis. It means the energy concenters on X-axis vibration.

3.3 Wavelet transform analysis

The vibration signal is analyzed by wavelet transform, and wavelet three-dimensional time-frequency of X-axis vibration is shown in Fig. 9. Compared to normal drilling, it is obvious that there is a peak at 20~25 Hz when stick-slip occurs. Meanwhile, the amplitude of low frequency is larger than normal drilling.

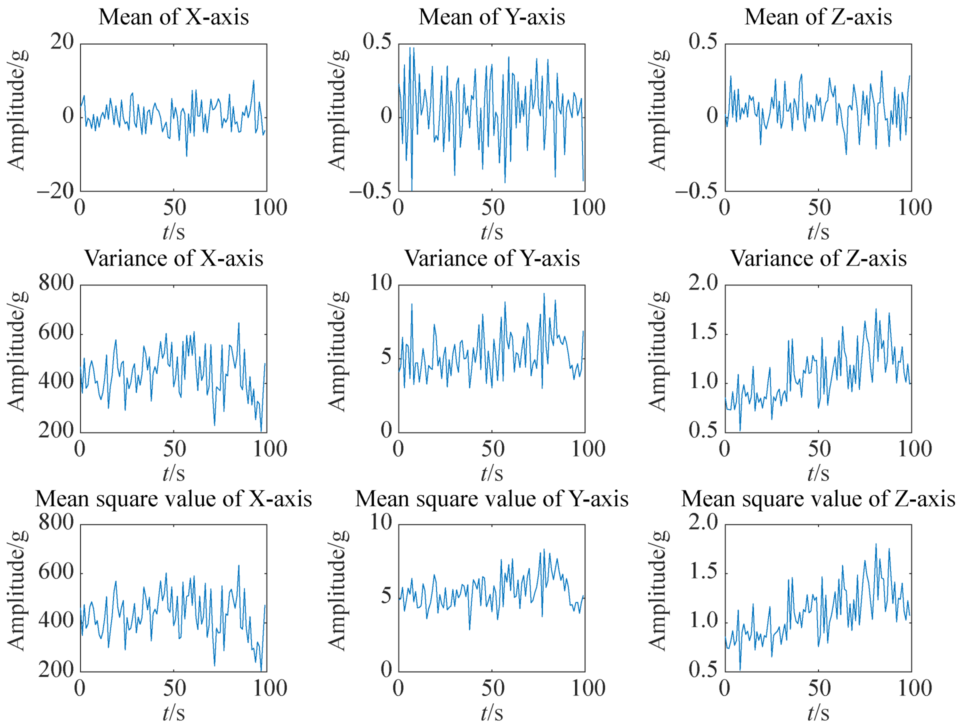
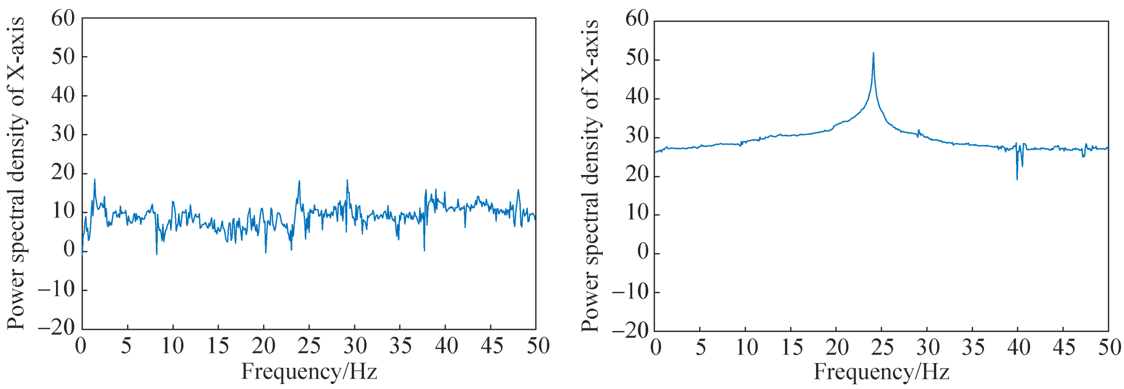
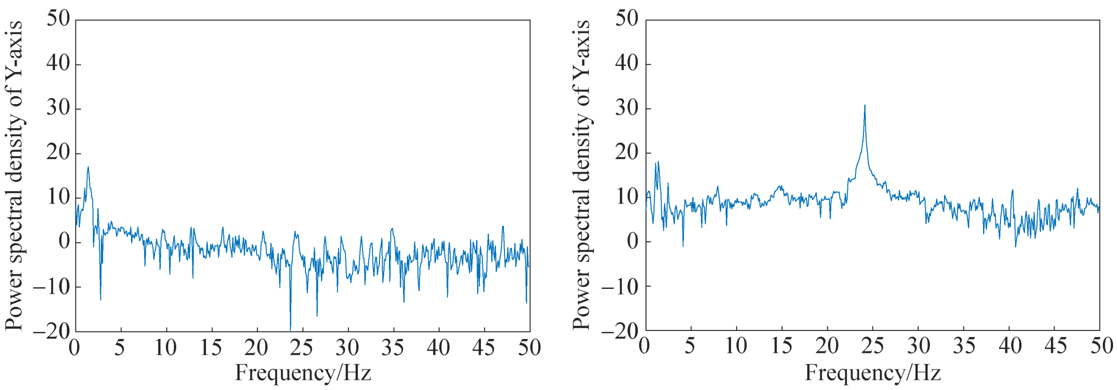


Fig. 6　Time domain analysis of stick slip



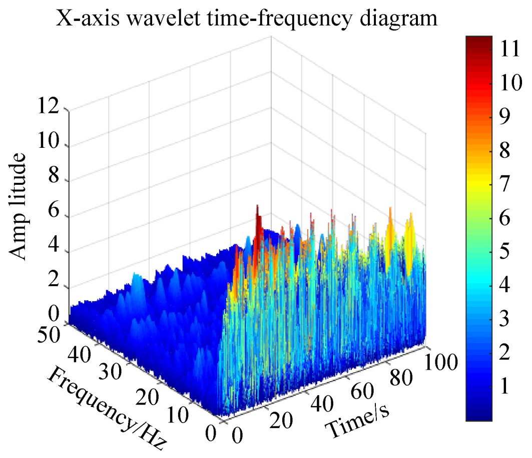
(a) Normal drilling　　　(b) Stick slip

Fig. 7　Power spectral density of X-axis

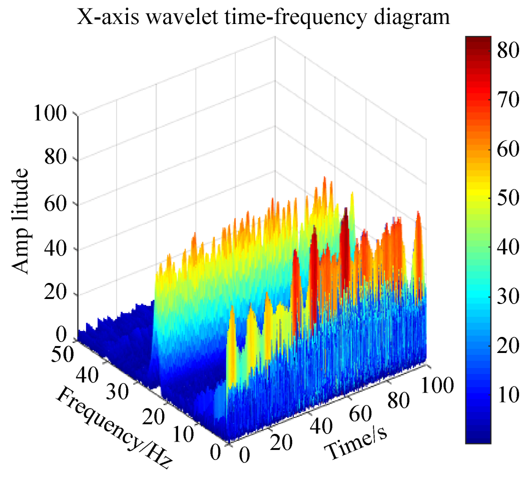


(a) Normal drilling　　　(b) Stick slip

Fig. 8　Power spectral density of Y-axis

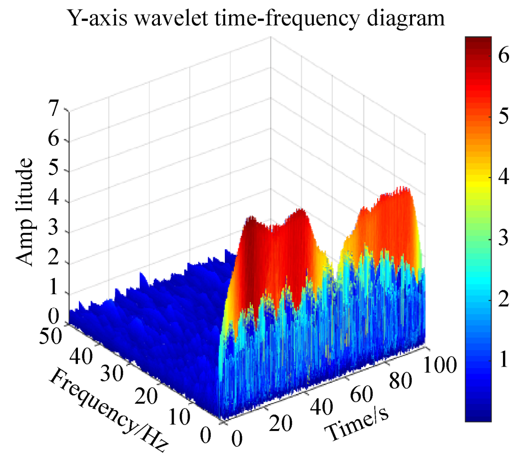


(a) normal drilling

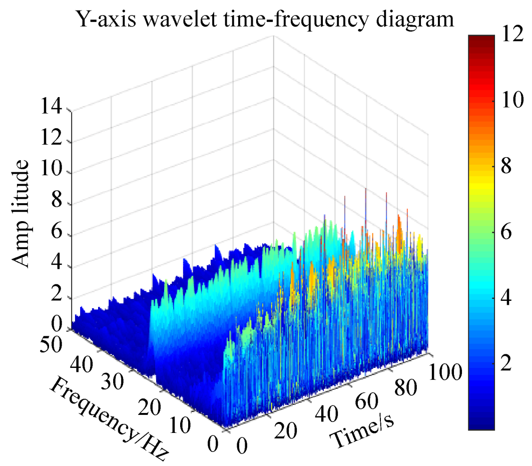


(b) Stick slip

Fig. 9 Wavelet transform analysis of X-axis



(a) Normal drilling



(b) Stick slip

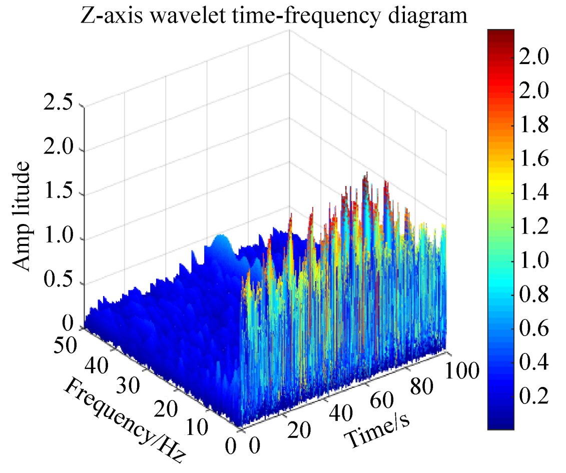
Fig. 10 Wavelet transform analysis of Y-axis

The three-dimensional time-frequency of Y-axis vibration wavelet transform is as shown in Fig. 10. Compared to normal drilling, there is a peak at 20~25Hz in Y-axis vibration wavelet transform. Meanwhile, the amplitude of Y-axis vibration wavelet transform is smaller when compared to X-axis at stick-slip. The difference between X and Y-axes is relatively large, indicating that when stick slip occurs, the torsional vibration is dominant.

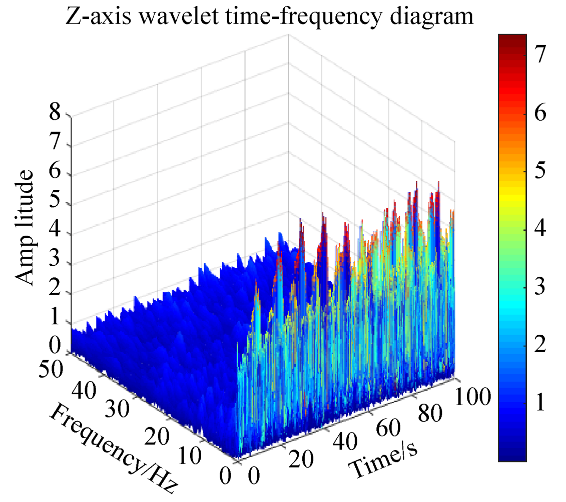
According to Fig. 9(a), Fig. 10(a) and Fig. 11(a), X and Y-axes,vibration wavelet transform has a distinct peak compared with Z-axis. And it shows further that explanation of stick-slip is mainly based on torsional vibration.

Conclusion from wavelet transform analysis comes to that: when stick slip occurs, lateral vibration is most susceptible at frequency of 0~5 Hz and 20~25 Hz, meanwhile, axial vibration at low frequency (Fig. 11).

During oil drilling process, the power spectral density and wavelet transform of the vibration signal can be calculated on the ground, and the driller judges whether stick slip occurs in the downhole according to the calculation results. When stick slip occurs, the driller decreases weight on bit (WOB) to mitigate stick slip.



(a) Normal drilling



(b) Stick slip.

Fig. 11 Wavelet transform analysis of Z-axis

4 Conclusions

From the perspective of signal processing, downhole stick slip vibration data is analyzed in time domain, frequency domain and time-frequency domain. By comparing with normal drilling situation, this paper draws following conclusions:

(1) The amplitude of three axial accelerations is stable during normal drilling, when stick slip occurs, the range of X-axis and Y-axis accelerations become larger. Meanwhile, the maximum amplitude of the lateral vibration is far greater than normal drilling, and mainly based on torsional vibration.

(2) The mean values of X-axis and Y-axis vibration differ large, which means stick slip mainly is based on torsional vibration.

(3) From the perspective of power spectral density analysis, the energy of the unit frequency is bigger than normal drilling.

(4) By wavelet transform analysis of stick slip and normal drilling vibration signal, conclusions come, stick slip occurs, while high amplitude of high frequency in lateral vibration, while high amplitude of low frequency in lateral vibration with normal drilling.

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