A Weak SNR Signal Extraction Method for Near-Bit Attitude Parameters Based on DWT

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Abstract: In practice, the near-bit signals are usually accompanied by noises generated by drilling tool vibration and high-speed rotary. This study introduces discrete wavelet transform to a well drilling area and presents a new weak signal extraction algorithm, which can eliminate the vibration and rotary noises effectively and obtain the useful gravity attitude signals based on the discrete wavelet transform through a hard threshold method. The effectiveness and usefulness of our method are verified via Matlab simulation and actual drilling data.

Keywords: near-bit attitude parameters; drilling tool vibration; high-speed rotary; weak signal extraction; discrete wavelet transform

1. Introduction

With the development of global oil/gas exploration, more and more attention are focused on unconventional oil/gas reservoirs, e.g., under ocean and deep and super-deep layers [1]. Oil/gas explorations have two problems to deal with. The first one is to enhance oil/gas recovery, to exploit difficult reserves, to develop remaining oil resources, and special economic marginal reservoirs such as low permeability, ultra-thin, heavy oil and ultra-heavy oil reserves, as well as scarce resources such as shale gas and coalbed methane, which requires the development of horizontal and directional drilling technology; The second one is to explore oil resources which are more and more concentrated in deep strata and deep-sea areas by vertical drilling of deep/ultra-deep wells. In exploration of oil/gas resources, steerable drilling is the key technology to solve these two problems [2].

The working principle diagram of the drilling system is given in Figure 1. It is crucial to have real-time, accurate, continuous, and dynamic measurements of downhole dynamic spatial attitude parameters (such as well inclination, azimuth, and tool surface angle, etc.) for real-time steering control of guided drilling tools. And it is common to use measurement while drilling (MWD) technology to obtain dynamic measurements of downhole attitude [3–5]. Its main characteristic is firstly to do well logging while drilling, then extract a real-time measurement of downhole attitude parameters, upload them to the ground, and finally, carry out feedback control of the downhole control system according to downhole attitude parameters to ensure dynamic stability of borehole trajectory.

However, practically the steering tool stability control platform connects both ends of the drill pipe and the bearing. The inertial components (acceleration sensors) are installed inside the steering tool stability control platform. Thus, rock cutting of the drill bit, as well as the collision of the drill string against the wall, and the high-speed rotation of the tool along with the drill string, will result in strong vibration signals and contaminate the dynamical measurements of the steering tool attitude parameters, which herein results in a large deviation when calculating attitude parameters while drilling and to a certain extent, could deteriorate the well trajectory control accuracy [5].
To deal with this problem, an unscented Kalman filter was proposed for the attitude of the rotary steering drill tool in [6], which effectively improves the accuracy of attitude measurements. Based on preset Euler rotation, a vertical attitude measurement method was given in [7], which can obtain the original signal amplitude of attitude measurement and reduce the solution error, a linearized model with the actual situation was presented to accurately describe the nonlinear factors and the stability control problem of the inertial navigation platform is solved in [8,9] after analyzing the inertial navigation platform of rotary steering drill. A non-orthogonal four-axis force accelerometer attitude measurement method was given in [10], which realizes the real-time measurement of downhole attitude of the modulated steering drilling tool. Through state space model for continuous real-time measurement of drilling trajectory, a new Kalman filter was presented to reduce the systematic error in [5]. A dynamic attitude measurement scheme of anti-differential adaptive filtering was conducted in [11] to handle the problem of attitude parameters uncertainty in dynamic measurement, and it uses the reasonable distribution information of equivalent weight function and adaptive factor to alleviate the drilling tool vibration influence on dynamic attitude measurement. Another multi-source dynamic attitude combination measurement method is proposed adopting the quaternion-based untracked Kalman filtering method to filter the vibration interference signals. The existing methods may inevitably damage the useful signals to a certain extent while removing noises based on the filtering scheme, which could lead to severe distortion of steerable drilling.

To improve the accuracy of attitude parameters, a new scheme is desired to effectively extract gravitational acceleration signals from the complex interferences. Wavelet transform is a local transformation of space (time) and frequency, so it can effectively extract information from data. Through the operation functions such as stretching and translation, the useful signal can be refined and analyzed at multiple scales. Various approaches based on the discrete wavelet transform (DWT) have been explored and used effectively in various areas, such as signal and image compression, statistics and numerical analysis [2,12–15] due to the powerful decomposition and reconstruction of DWT. However, few results have been reported in near-bit signal processing areas. We proposed a new method based on DWT in [16] to deal with the extraction of near-bit weak signal noise ratio (SNR) signal. In this paper, we will give more details of our scheme through a hard threshold to improve the accuracy of attitude parameters for steerable drilling control and conduct actual drilling well data to verify our method.

After analyzing the characteristics of the original weak signals contaminated by strong vibration and rotary, we first decompose the original near-bit measured data, then cut
off the detailed coefficients using a threshold, which is adaptively designed, and finally reconstructs the data. Daubechies 5 (Db5) is adopted at a suitable level of decomposition.

This paper is organized as follows. In Section 2, backgrounds and basic characteristics of the near-bit signals are given. Section 3 introduces the DWT algorithm, and presents details of our proposed extraction scheme using a hard threshold. Then Matlab simulation verification and actual experiments results are given in Section 4 to illustrate the utility and effectiveness of our extraction algorithm. Conclusions are contained in Section 5.

2. Backgrounds

We will discuss the influence of near-bit vibration and tool rotation on attitude parameter measurements and the calculation process of attitude parameter measurement.

2.1. Static Drilling and Dynamic Drilling

Traditionally the sensor probe distance is far away from the bit and drilling tools to weaken the interference affection of vibration and tool rotary on the measurement accuracy. Thus, the real-time trajectory can not be measured in static drilling. Taking the accelerometer along $x$ axis, for example, its output is the element of gravity

$$S_{x}^{\text{static}} = g_x$$  \hspace{1cm} (1)

Without stopping drilling, dynamic measurements could provide real-time and dynamic data of the drilling tool. However, in dynamic near-bit measurement processing, the output of each accelerometer consists of not only the components of gravity, but also the centrifugation acceleration resulting from the instrument rotation, vibration acceleration and impact acceleration when drilling. In dynamic measurement of the output of each accelerometer can be described by [17]

$$S_{x}^{\text{dynamic}} = g_x + v_x + r_x$$  \hspace{1cm} (2)

where $g_x$ is the component of gravity acceleration, $v_x$ is the vibration acceleration caused by strong vibration, $r_x$ is the centrifugation acceleration resulted from high-speed rotary, along $x$ axis, respectively. It is crucial to effectively obtain $g_x$ from the contaminated measurement signals to improve the dynamic measurement accuracy.

2.2. Influence of Near-Bit Vibration on Attitude Parameters Measurements

The near-bit vibration signals have three characteristics: (1) the high- frequency characteristic formed by the teeth of the roller bit penetrating the rock; (2) the broadband characteristic of near-bit vibration; (3) the randomness characteristic of the compound motion formed by the bit teeth, roller and bit.

The amplitude of useful measurement signals are the components of gravity acceleration, which is less than $g$ ($g$ is gravity acceleration, $9.8 \text{ m/s}^2$). However, the amplitude of near-bit vibration signal is generally around $10 \, g$, and sometimes can reach the maximum value $30 \, g$ [7,18]. Therefore, the vibration acceleration signals near the drill bit are usually dozens of times than the gravity acceleration, and thus overwhelm the weak gravity acceleration signals, leading to noneffective attitude measurements.

Figure 2 shows the logging data of a well with a depth of 1740–1807 m in the west of Sichuan province, China, between 20 November and 24 November 2014. The measured well inclination angle is around $2.5^\circ$, and the high side tool face angle is basically stable at around $100^\circ$. However, as clearly demonstrated in Figure 2, the strong vibration near the drill bit introduces massive high-frequency and high amplitude noises.
2.3. Effect of High-Speed Tool Rotation on Attitude Parameter Measurements

When the guiding drilling tool rotates, given $\delta a_x, \delta a_y$ the measurement error of the accelerometer along $x$ axis and $y$ axis respectively, the accelerations $a_x$ and $a_y$ of the equivalent mass blocks along $x$ axis and $y$ axis are,

$$a_x = g_x + \omega_x$$

$$= g \sin \theta \sin \phi + \frac{d\omega}{dt} R + \delta a_x \quad (3)$$

$$a_y = g_y + \omega_y$$

$$= g \sin \theta \cos \phi + \omega^2 R + \delta a_y \quad (4)$$

where $g_x$ and $g_y$ are the components of the gravity acceleration along $x$ axis and $y$ axis respectively; $\omega_x$ is the acceleration of the tangential additional inertial force along $x$ axis, which varies with the change rate of the rotation velocity $\omega$; $\omega_y$ is the acceleration of the centrifugal force along the $y$ axis, which varies with the square of the rotation velocity $\omega$; and $\theta$ and $\phi$ are well inclination angle and tool face angle respectively.

According to (1) and (2), when the rotation speed $\omega$ of the guiding drilling tool is relatively high, the gravity accelerometer installed on the drilling tool will have significant measurement noises in the different orientations of the borehole, leading to severe errors in attitude parameters measurements of the guiding drilling tool.

3. New Scheme for Gravity Acceleration Signals Extraction Based on DWT

3.1. Discrete Wavelet Transformation

Wavelet transform is a tool to study the components of the corresponding scale by using the decomposition method, which separates the data, function, or different operating frequency components. The key of wavelet transformation is a variable analysis window of time-frequency. With the window, its wide part can be used to analyze the low-frequency signal and its narrow part can be used to analyze the high-frequency signal. Therefore, wavelet transformation can provide the superior time-frequency resolution for signal analysis within all the frequency scope [19]. The ideas and foundations behind DWT come from multi-resolution analysis [12,13].

Wavelet denoising techniques were initially developed in [20] for white noise reduction. In the basic wavelet denoising, a non-linear processing is made in the wavelet domain (usually thresholding), and a reconstruction is obtained by the inverse transform. The fundamental equation in wavelet transform is given as

$$f(t) = \sum_{k=-\infty}^{+\infty} c_k \phi_k(t) + \sum_{j=-\infty}^{+\infty} \sum_{k=-\infty}^{+\infty} d_{jk} \psi_{jk}(t) \quad (5)$$
where \( f(t) \) produces the converging series of values, the parameters \( c_k \) are the approximation coefficients, and \( d_{l,k} \) are the detail coefficients.

As high-frequency components can reflect more details of signals, they are more suitable for extracting the submerged signals from hyperspectral reflectance.

### 3.2. Calculation Procedure of Attitude Measurement Parameters

Measurement while drilling (MWD) systems usually use three gravitational acceleration sensors along \( x, y, \) and \( z \) axes to measure the inclination angle and tool-face angle. The coordinate system \( xyz \) is given in Figure 3. Right-handed cartesian coordinate consists of \( z \) axis along the axis of the drilling tool, \( x \) axis along the radial direction, and \( y \) axis along the tangent direction. Three-axis acceleration sensors are installed along \( x, y, \) and \( z \), respectively.

![Figure 3. Schematic diagram of multi-sensor combination measurement.](image)

The inclination angle is the angle between the axis of the drilling tool and the plumb line varying from 0 degrees to 180 degrees. Its measurement is based on the variation of gravity components along the well axis and the plumb line as the inclination changes. We can measure the gravity components along the \( x, y, z \) axis using three orthogonal acceleration sensors and then calculate the value of inclination angle \( \theta \) by

\[
\theta = \arctan \sqrt{\frac{g_x^2 + g_y^2}{g_z}}
\]

and calculate the tool-face angle by

\[
\phi = -\arctan \left( \frac{g_y}{g_z} \right)
\]

As we can see from above, if the measurements, \( g_x, g_y, g_z \), of acceleration sensors are contaminated by near-bit vibration and high-speed rotation signals, we are not able to obtain exact attitude parameters, and thus will not accurately control the guiding drilling tool.

### 3.3. Proposed Extraction Scheme Based on DWT

It is very difficult to extract the weak attitude parameters signal from the measured signals contaminated by strong vibration and rotary directly. The signal processing method based on wavelet transform theory has the power to deal with this problem properly. The DWT algorithm has received considerable attention in various signal processing applications. Different wavelet bases satisfy different requirements of signal processing. Here we choose Daubechies wavelets as the base wavelet, which are a family of orthogonal wavelets defining a discrete wavelet transform and characterized by a maximal number of vanishing moments.

Here we propose the extraction scheme based on DWT adopting hard threshold, which firstly reconstructs the original signal through wavelet transform and then inverse transforming the wavelet coefficients. The scheme is simple and effective.
Firstly, we decompose the original signal. In this process, when designing the threshold, we choose the hard threshold method. The steps of our scheme are as follows. Here we adopt Daubechies wavelets (Db5) as the wavelet base. Take $g^m_x$ along $x$ axis for example,

Step 1. Apply DWT and decompose the demanded signals, $g^m_x$, in which vibration and rotation noises are contained, into wavelets with different scales.

\[ g^m_x \approx \sum_{k=1}^{5} c_k \phi_k(x) + \sum_{j=1}^{5} \sum_{k=1}^{5} d_{j,k} \psi_{j,k}(x) \]  \hspace{1cm} (8)

where $m$ denotes measurements.

Step 2. Obtain the detail coefficients $c_k$ and approximation coefficients $d_{j,k}$.

Step 3. Apply hard threshold method and set the high-frequency detail coefficients to be the designed value.

In common wavelet de-nosing methods, the threshold de-noising method deals with all level coefficients based on the corresponding strategy that is over or below a certain threshold value after performing a wavelet transform separately and inverse transforming the corresponding wavelet coefficients. Different threshold functions could reflect different strategies of wavelet coefficients greater or smaller than the given threshold value. Here we choose the hard threshold method for simplicity. In hard threshold, the absolute values of the decomposed coefficients will be compared with the specified threshold. If the compared result is smaller than or equal to the threshold, let it be zero, else the coefficients will remain.

Step 4. Based on $c'_k$ and $d'_{j,k}$, calculate $\hat{g}_x, \hat{g}_y, \hat{g}_z$

\[ \hat{g}_x \approx \sum_{k=1}^{5} c_k \phi_k(x) + \sum_{j=1}^{5} \sum_{k=1}^{5} d'_{j,k} \psi_{j,k}(x) \]  \hspace{1cm} (9)

where $\hat{g}_x$ is the estimated signal of $g_x$.

Step 5. Based on (6) and (7), get the two angles, inclination angle and tool-face angle, respectively.

Thus, the near-bit dynamic attitude parameters (well inclination angle, azimuth angle, and tool surface angle, etc.) will be extracted and the noises resulting from drilling tool vibration and high-speed rotary will be filtered well. Although the selection of wavelet basis has a significant influence on the results of the whole wavelet analysis without adaptability, it is simple to implement and has low calculation.

We will verify the effectiveness and accuracy of our proposed extraction scheme via MATLAB simulation data and actual drilling data from a well in China respectively.

4. Performance Evaluation and Discussion

4.1. Verification of Our Extraction Algorithm via MATLAB Simulation

Firstly, the effectiveness and accuracy of our proposed extraction scheme will be verified via MATLAB simulation where the extraction method based on DWT is denoted as EDWT and the classical low pass filter is denoted as LPF.

Here, the well inclination angle is $30^\circ$, the tool rolling frequency is 150 $\tau$/min, and the sample frequency is 203.45 Hz with 1000 points. Generate the outputs of three accelerometers along three axes and wide-band white noises with different amplitudes as the vibration disturb. Meanwhile, add DC bias to the $x$ and $y$ axis to simulate the centrifuge and tangential accelerations. Accordingly, Figure 4 shows the contaminated true effective signals along the time axis, which will result in a large deviation when calculating attitude parameters.

As shown in Figure 5, the filtered signals $\hat{g}_x, \hat{g}_y, \hat{g}_z$ using the proposed method are given. The filtered signals using EDWT are apparently smoother than that using LPF setting the threshold at 30 Hz, and the biases of measurements along $x$ and $y$ axis have been removed. From the filtered results, we can see that our method is effective in extracting the gravity acceleration signals from vibration and rotation noises.
Figure 4. Measured components of gravity acceleration along three axis.

Figure 5. Filtered components based on Db5.

Figure 6 shows the filtered inclination angles together with the true inclination angle using EDWT and LPF. Our filtered inclination angle error is between +5° and −5°. The filtered results of tool-face angle are given in Figure 7, and our results clearly outperform that of LPF, which means our method takes the acceleration signals and eliminates the noises effectively.
Our proposed method is powerful and effective through MATLAB simulation data verification.

4.2. Verification of Our Extraction Algorithm via Actual Drilling Data

In this section, we conduct actual drilling data from a certain well in China to validate the effectiveness of our method.

Figure 8 gives real measurements of three-dimensional accelerometers from some drilling well in China. Drilling depth is 1768 m, drilling velocity is 45 r/min and the total drilling time period is 75 h. The data are measured voltage signals along x, y, z axis, respectively.
Figure 8. Actual measurements of gravity components along three axes.

Using the measurements, we cannot obtain accurate parameters due to multiple sources of noise. From Figure 8 we can see that the original measurements curve has a large fluctuation range with noise, and signals along the x-axis are damaged by noises worst.

Figure 9 shows the filtered signals along x, y, z axis respectively acquired by our proposed method as well as LPF, where high-frequency noises are eliminated. The processed data along x axis has been obtained, and we can even see its peak is at 40 s. For the signals along the y axis, there is a peak at around 120 s. This is because there is a severe trough in the original curve as shown in Figure 8, and the signals are recovered using the proposed method when we reconstruct signals based on (9).

Figure 9. Filtered measurements of gravity components along three axes.

Then based on (6) and (7), the plots of inclination angle measurements and filtered inclination angles are given in Figure 10. We can see that the filtered curve using EDWT is flat and steady with accuracy between ±2°.
The comparison of tool face angle measurements and filtered tool face angle plots are given in Figure 11. The tool face angle using EDWT is around 317° with accuracy between ±5°.

5. Conclusions

In this paper, DWT is introduced to the well drilling area and a new scheme to extract the weak signal from the down well is proposed, which is simple to apply. The original weak signals contaminated by strong vibration and rotary are finally constructed. Then the proposed method is validated by simulation experiments and actual well data, which proves its effectiveness and usefulness. The proposed method can be expanded to the area of inclination dynamic measurement for at-bit geosteering system or rotary steerable
drilling system after actual drilling environmental data testing, and could bring possible economic effects to the oil drilling industry. Here the selection of wavelet basis has a significant influence on the results of the whole wavelet analysis, and we will make more efforts to deal with its adaptability in future.

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