LMS Adaptive Filtering of Drilling Tool Vibration Signal

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Abstract: As the dynamic measurement of attitude parameter of the steerable drilling tool under vibration may be not accurate, the Least Mean Square (LMS) adaptive filtering algorithm is adopted to filter the influence of drilling tool vibration on the attitude measurement in this paper. The simulation results show that the measurement error of inclination angle after LMS adaptive filtering can be less than 0.1°, and the measurement error of tool face angle is less than 6°, which could effectively improve the attitude measurement accuracy of vertical steerable drilling tools; the results of inverse analysis on actual drilling data show that the actual measurement error of inclination angle after LMS adaptive filtering is about 3°, which is much smaller than that before filtering. It shows that LMS adaptive filtering can effectively filter the vibration signal of drilling tools and greatly improve the dynamic measurement accuracy of the tool attitude.

1. Introduction

The vibration of drilling tools is generally divided into lateral vibration, longitudinal vibration and torsional vibration, while lateral vibration is the main vibration of drilling tools [1]. During actual drilling process, the strong vibration of the bottom drilling tool seriously disturbs the attitude measurement of the accelerometer, resulting in serious distortion of the attitude parameter, which may seriously affect the straightening and make the hole trajectory uncontrollable [2]. Liu Baiyan etal. have studied the static and dynamic measurement of the inclination angle based on gravity accelerometer [3], they have filtered part of the vibration influence with low-pass filter circuit, then further filtered the influence of residual vibration and AC noise of the sensor with Butterworth low-pass digital filter, finally they proposed the attitude dynamic measurement scheme of the tool and validated the scheme by experiments combining with speed correction [4]. However, they have only performed experimental study other than actual drilling test. The author has performed actual drilling test with this dynamic measurement method and found that there are still large errors in attitude parameter measurement due to high frequency and high amplitude vibration of the near-bit, which could not meet the requirements of steerable control.

In this paper, the author has studied LMS adaptive filtering, and proposed to eliminate the influence of near-bit lateral vibration on the dynamic measurement of attitude parameter with LMS adaptive filtering, so as to improve the calculation accuracy of attitude parameter.

2. Attitude Measurement of Vibrating Tools

During normal drilling of the steerable drilling tool, cutting rocks by the drill bit will cause lateral vibration, longitudinal vibration and torsional vibration of the downhole drilling tool, and the lateral vibration is particularly obvious [5]. The lateral vibration of bottom hole assembly of the steerable
drilling tool has three characteristics, namely high frequency, broadband and randomness [6], and its amplitude is generally about 10g (g is the gravity acceleration, \(9.8\ m/s^2\)), the maximum can reach 30g [7]. In order to facilitate the system simulation analysis, a random white noise with an amplitude of 6g is used to simulate the high-frequency random vibration signal of the drilling tool according to the lateral vibration signal characteristics of the bottom hole assembly in this paper, and the signal characteristics are as shown in Figure 1.

![Figure 1 Near-bit vibration signal simulation](image)

If only the lateral vibration of the drilling tool is considered, then the vibration acceleration on X-axis and Y-axis accelerometers is recorded as \(A_x\) and \(A_y\) respectively after the accelerometer acceleration is decomposed along X-axis and Y-axis. Let \(A_x = K_xg\), \(A_y = K_yg\); \(K_x\) and \(K_y\) are the random coefficients with a maximum of 10. Assuming that the influence of near-bit vibration and gravity acceleration on the accelerometer is linear additive, then the measurement signals of X-axis and Y-axis gravity accelerometers are

\[
\hat{V}_x = V_x + V_{px} = V_g \sin \theta \sin \varphi + K_x V_g
\]

\[
\hat{V}_y = V_y + V_{py} = V_g \sin \theta \cos \varphi + K_y V_g
\]

(1)

(2)

Where, \(V_x, V_y\) are ideal output signals of the accelerometers, \(V_{px}, V_{py}\) are additional signals generated by the vibration, \(V_g\) is accelerometer full-scale output, \(\theta\) is tool inclination angle, and \(\varphi\) is tool face angle.

Generally, the vibration acceleration of the drilling tool is much larger than gravity acceleration. It can be known from equations (1) and (2) that the weak gravity acceleration signal will be annihilated in the lateral vibration acceleration noise of the drilling tool, resulting in invalid attitude measurement of the tool. In this regard, LMS adaptive filtering is used to filter the vibration signal of drilling tools to improve attitude measurement accuracy.

3. LMS Adaptive Filtering of Vibration Signal

The near-bit vibration signal is a broadband noise signal. The adaptive filter plays its advantages of automatic parameter adjustment to automatically track the noise source to filter out the noise without knowing the input signal and noise statistical characteristics [8]. The basic idea of adaptive filtering is to offset the vibration signal by reference signal estimated by the filter [9].

The adaptive filter has two inputs, the one is original channel, which not only receives the accelerometer measurement signal \(V_r(k)\), but also receives the near-bit vibration additional signal \(V_{nr}(k)\) uncorrelated with the signal \(V_r(k)\). The other one is a reference input channel which receives the vibration signal \(V_{nr}(k)\) uncorrelated with signal \(V_r(k)\) but correlated with vibration signal \(V_{nr}(k)\), and its structure is as shown in Figure 2. According to the characteristics of the adaptive filter, after the output of vibration signal \(V_{nr}(k)\) automatically adjusted by the LMS adaptive filter [10], the estimated signal of \(V_{nr}(k)\) is obtained, i.e.

\[
y(k) = \hat{V}_{r_{nr}}(k)
\]

(3)

Where, \(y(k)\) is the output value of the filter. Then the error signal \(e(k)\) from the adaptive filter system is the difference between the original signal and reference input signal, namely:

\[
e(k) = V_r(k) + V_{nr}(k) - \hat{V}_{nr}(k)
\]

(4)
Square the left and right sides of equation (4):
\[ e^2(k) = V_x^2(k) + [V_{sp}(k) - V_{rp}(k)]^2 + 2V_x(k)[V_{sp}(k) - V_{rp}(k)] \]

Take the mean square error of equation (5):
\[ E[e^2(k)] = E[V_x^2(k)] + E[(V_{sp}(k) - V_{rp}(k))^2] + 2E[V_x(k)(V_{sp}(k) - V_{rp}(k))] \]

In equation (6), \( E[e^2(k)] \) refers to the power signal, and \( V_x(k) \) is uncorrelated with \( V_{sp}(k) \), namely
\[ 2E[V_x(k)(V_{sp}(k) - V_{rp}(k)) = 0 \]

Therefore, the mean square error \( E[e^2(k)] \) reaches the minimum when the mean square error \( E[e^2(k)] \) is minimum.

\[ W(k+1) = W(k) + 2\mu e(k)x(k) \]

Therefore, under LMS criterion, \( E[(V_{sp}(k) - V_{rp}(k))^2] \) is minimized, i.e. the approximation of output \( y(k) \) of the LMS adaptive filter to \( V_{px1}(k) \) is equivalent to approximation of \( e(k) \) to \( Vx(k) \), so that the system outputs the optimal estimation of accelerometer signal \( Vx(k) \).

4. System Simulation Analysis

4.1 System simulation structure

Based on the static calculation equation of attitude parameter of the steering tool (the measurement error of the accelerometer is 5%), the vibration signal of the drilling tool is added and the tool face angle is fed back to the previous moment. The simulation system structure is as shown in Figure 3.
The drilling tool is constantly rotating and moving during actual drilling process, and the tool face angle changes with tool rotation, thus the tool speed \( \omega \) is used as the input of simulation system. Specify the constant speed of the drilling tool \( \omega \) (assuming that the constant speed of the drilling tool has little effect on the attitude measurement, which can be negligible) and near-bit vibration signal, and let the inclination angle \( \theta = 0.3^\circ \) and the initial tool face angle \( \phi_0 = 0^\circ \). The recursive calculating formula of tool face angle is

\[
\phi_{i+1} = \phi_i + \omega T
\]  

(9)

Calculate the theoretical output signal \( \dot{V}_x, \dot{V}_y \) of the acceleration sensor from the set tool attitude parameter, add the vibration signal to signal \( \dot{V}_x, \dot{V}_y \) according to equations (1) and (2) to obtain the estimated accelerometer values of three axes \( \hat{V}_x, \hat{V}_y \), then filter the estimated value of the tool attitude parameter by reversing the calculation formula of tool attitude parameter, finally reserve the tool face angle \( \hat{\phi} \) (with delay of 1s), and calculate the new tool face angle with formula (9) for the next round of simulation analysis.

4.2 System simulation analysis

As the simulation model is built by the system simulation structure when the constant speed of steering tool \( \omega = 2\pi \) (rad/s) and the deviation angle \( \theta = 10^\circ \), the simulation results are as shown in Figures 4 and 5.

![Fig.4 Theoretical value and filtered value of inclination angle when \( \omega=2\pi \) (rad/s) and \( \theta=10^\circ \)](image)

![Fig.5 Theoretical value and filtered value of tool face angle when \( \omega=2\pi \) (rad/s) and \( \theta=10^\circ \)](image)

It can be seen from Figure 4 and Figure 5 that when the drilling is under vibration condition, the measurement error of tool attitude parameter is extremely large. While after LMS adaptive filtering, the measurement error of the inclination angle is about 1.5° and it is approximately 10° for that of tool face angle, both are much smaller than those before filtering. It can be seen from the simulation results that the adaptive filter greatly improves the measurement accuracy of steering tool attitude parameter with remarkable improvement on measurement performance.

5. Actual Drilling Data Inversion

The original data of a vertical steerable drilling system of the well in western Sichuan on January 23, 2016 is used for inverse analysis in this paper. Drilling condition of the system: downhole temperature of 38°C around, drilling pressure of 10 Mpa around, pump pressure of 6.6 Mpa around, hang weight of...
79 KN; downhole operation time of 75 h, tool speed of 45 rpm around. The steering tool is stable and straight during drilling, and the inclination angle $\theta$ is controlled at about 3°. The data acquired by the accelerometer is stored once per 20 s. The original measurement data of X-axis, Y-axis and Z-axis accelerometers are as shown in Figure 6, and the measured inclination angle is as shown in Figure 7.

![Measured data of X-axis, Y-axis and Z-axis accelerometers](image1)

**Fig. 6 Measured data of X-axis, Y-axis and Z-axis accelerometers**

![Measured inclination angle](image2)

**Fig. 7 Measured inclination angle**

Convert the measured data of X-axis, Y-axis and Z-axis accelerometers in Figure 6 into a voltage signal with the existing formula in accelerometer angle conversion program, and calculate the angle of such voltage signal to obtain the measured inclination angle (as shown in Figure 7) with a maximum of 28.41° due to the strong downhole vibration, which will seriously affect the stable and straight operation and straightening effect of the drilling tool. Therefore, the author proposes to eliminate the effect of vibration signal on the measured data of X-axis, Y-axis and Z-axis accelerometers with LMS adaptive filtering in this paper. The measured data and filtered data of X-axis, Y-axis and Z-axis accelerometers are shown in figures 8-11.

![Comparison of measured data and filtered data of X-axis accelerometer](image3)

**Fig. 8 Comparison of measured data and filtered data of X-axis accelerometer**
According to the data of X-axis, Y-axis and Z-axis accelerometers obtained by LMS adaptive filtering, the inclination angle of the tool is calculated from the angle calculation formula in accelerometer angle conversion program. The comparison of measured inclination angle and filtered inclination angle is as shown in Figure 12.

When the steering tool is under stable and straight condition, the actual measured value of the inclination angle $\theta$ fluctuates greatly. The maximum measured value is $28.41^\circ$ with an error up to $25^\circ$ around, and the minimum measured value is $0.32^\circ$ with an error up to $2.5^\circ$ around. After filtering the accelerometer measurement signal with LMS adaptive filter, the maximum inclination angle is $6.6^\circ$ around with an error of $4^\circ$ around; the minimum inclination angle is $0.6^\circ$ with an error of $2^\circ$ around. Obviously, the measurement error of steering tool inclination angle can be significantly reduced after LMS adaptive filtering, which can effectively improve the stable and straight effect of the steering tool.
Comparison between the measured data of Z-axis accelerometer and the filtered data shows that the near-bit vibration is lateral vibration at this moment, which has little effect on Z-axis accelerometer and can be ignored. Therefore, the Z-axis data is not filtered in case of angle calculation. In addition, the author also verifies the near-bit vibration characteristics by angle calculation after filtering the measured data, which has fully demonstrated the high frequency, broadband and randomness of the vibration.

Notes: ① The tool face angle is not explained in the inverse analysis of actual drilling data since there is no reference for the tool face angle during actual drilling. ② The actual drilling data involved in this paper has a storage cycle of 20 s, then the maximum measurement error of inclination angle after filtering is up to 4° due to such relatively long cycle.

6. Conclusion

Dynamic measurement problem of the attitude parameter of vertical steerable drilling tool under vibration can be effectively solved by LMS adaptive filter. It can be known from the results of inverse analysis on actual drilling data that the measurement error of inclination angle is about 3° after the accelerometer measurement signal is filtered by LMS adaptive filter, which could effectively filter out the near-bit vibration signal and greatly improve the dynamic measurement accuracy of vertical steerable drilling tool with remarkable improvement on measurement performance. Additionally, the comparison of measurement signal of Z-axis accelerometer before and after filtering shows that the near-bit vibration is mainly lateral vibration, and the lateral vibration features high frequency, randomness and broadband.

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