**TELKOMNIKA**, Vol. 11, No. 6, June 2013, pp. 3028 ~ 3035
e-ISSN: 2087-278X



# Eliminating Noise of Mud Pressure Phase Shift Keying Signals with A Self-Adaptive Filter

**Yue Shen*[1], Lingtan Zhang[2], Heng Zhang[3], Yinao Su[4], Limin Sheng[5], Lin Li[6]**
[1,2,3]School of Science, China University of Petroleum, Qingdao, 266580, P. R. China
[4,5,6]Drilling Technology Research Institute, CNPC, Beijing, 100195, P. R. China
*Corresponding author, e-mail: sheny1961@yahoo.com.cn*[1], zhanglt@upc.edu.cn[2], zhang66h@163.com[3], suyinao@petrochina.com.cn[4], slmdri@cnpc.com.cn[5], lilin550703@yahoo.com.cn[6]

***Abstract***

*The feasibility of applying a self-adaptive filter to eliminate noise in the downhole mud pressure phase shift keying (PSK) signals is studied. The self-adaptive filter with carrier wave as the filter input signal and mud pressure PSK signal including noise as the filter expected input signal in structure was adopted to process the mud pressure PSK signals with the broadband signal characteristic in communication. Mathematical model of the filter was built to reconstruct the mud pressure PSK signals based on the evaluation criterion of least mean square error (LMS) and the mathematical model of mud pressure PSK signals. According to the filter mathematical model, a special self-adaptive control algorithm was adopted to realize the filter by adjusting the filter weight coefficients self-adaptively and the impacts of the filter step-size factor on signal to noise ratio (SNR) and distortion factors of the reconstructed mud pressure PSK signals were analyzed. Numerical calculation and simulation show that the self-adaptive filter can efficiently eliminate random noise in the signal frequency band and reconstruct the mud pressure PSK signals. In addition, low distortion factors of the reconstructed mud pressure PSK signals can be obtained by reasonable selecting the filter step-size factor.*

***Keywords****: self-adaptive filter, mud pressure phase shift keying signal, noise, carrier wave*



## 1. Introduction

Measurement While Drilling (MWD) consists of making various downhole measurements and then transmitting this information to the surface for display and further interpretation or immediate use. One of the most common methods of passing the information from the downhole sensors to the surface is through pressure pulses in the mud flow, a technique known as mud pulse telemetry. The newer mud pulse telemetry uses a mud siren type of modulator to generate mud continuous pressure wave signals and allows complex modulation methods to be used to produce higher data rates by accurate control of the phase or freqency of the mud siren, the modulation method is called phase shift keying (PSK) modulation. Modulation type such as differential phase shift keying (DPSK) and even more complex modulation method such as quadrature phase shift keying (QPSK) can be used to generate mud pressure PSK signals to transmitting in mud with a mud siren modulator. In MWD system, the principal noise source is the pressure fluctuations caused by bit vibration, downhole motor stalling or drill string buckling and the noise presents a band-limited white Gaussian noise due to the lower noise frequency spectrum [1]. Though frequency of the noise source is not high, there is still some noise into the signal frequency band, causing relatively larger random pressure fluctuating in amplitude and making signal to noise ratio (SNR) of the downhole mud pressure signal severely reduce. Due to spectrum aliasing of noise and the mud pressure signal, conventional signal processing methods cannot effectively eliminate or suppress the noise. Some researchers put forward the matched filter method to eliminate the noise effects by calculating the self-correlation coefficients of signal mixed with noise based on the difference of noise and signal in correlation [2], but this method is only suitable for limited single frequency signal modulated by the frequency shift keying (FSK) method having low transmission efficiency and not for the frequency band signal modulated by mud pressure PSK method. An adaptive compensation method [3], proposed by Brandon etc., can eliminate theoretically noise in the MWD signal by extracting appropriate proportion of the signal mixed with noise as reference

*Received January 9, 2013; Revised March 16, 2013; Accepted April 12, 2013*

input signal of the adaptive compensator and automatical adjusting the noise intensity by feedback of output signal to balance noise of MWD signal, but it is difficult to implement and the effect is limited. According to the frequency band transmission characteristics of mud pressure PSK signals and mathematical theory of self-adaptive filter, a mathematical model of the self-adaptive filter with a carrier wave as reference input signal and MWD signal mixed with noise as the expected input signal is built for processing the mud pressure PSK signals with broadband signal characteristic, and the feasibility of eliminating noise in the mud pressure PSK signals based on self-adaptive filtering method is also studied in this paper.

## 2. The Mathematical Model of Self-adaptive Filter

### 2.1. The Structure of Self-adaptive Filter

Self-adaptive filter is a kind of digital filter based on modern adaptive control theory [4, 5], it can be used to realize dynamic tracking and noise elimination of the signal by self-adaptive adjusting the filter parameters according to the signal features. Self-adaptive filter is commonly used in processing narrow band signal in radio communication system, in which the ratio between signal frequency band and carrier wave frequency is greatly less than 1 and signal frequency in frequency band has little change comparing with carrier wave frequency. Figure 1 is the general structure of adaptive filter, in which $x(n)$ is input signal with noise, $d(n)$ is expected signal input, $y(n)$ is the filter output, and $e(n)$ is error signal output. The expected signal is special signal reflecting the feature of extracted signal. Under the effect of error signal, the self-adaptive filter adjusts the filter coefficients self-adaptively and the output signal continuously approaches to the expected signal to make the error minimal eventually, and the effective characteristic included in the input signal is dynamically extracted, then the useful signal reconstruction and noise elimination or suppression will realize.

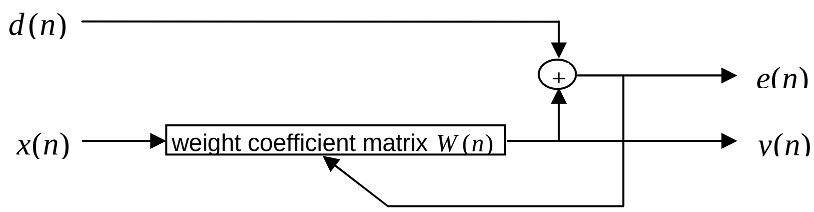


Figure 1. The structure of self-adaptive filter

According to the linear system theory, the self-adaptive filter output matrix $Y(n)$ is convolution of the input matrix $X(n)$ and unit impulse response matrix $H(n)$ and can be shown as follows.

$$Y(n) = X(n) * H(n) \tag{1}$$

Comparing with conventional digital filter structure with fixed parameters, the self-adaptive filter parameters form a weight coefficient matrix $W(n)$ with $1 \times \mathrm{N}$ dimension. If the input matrix $X(n)$ is $\mathrm{N} \times 1$ dimension, then the output matrix $Y(n)$ of the self-adaptive filter can be expressed as:

$$Y(n) = W(n)X(n) = y(n) = \sum_{i=0}^{\mathrm{N}-1} w_i(n)x(n-i) \tag{2}$$

Where, $n$ and $i$ are discrete variables, $W(n)$ is weight coefficient matrix of the self-adaptive filter, $w_i(n)$ is matrix coefficient of $W(n)$, $x(n-i)$ is matrix coefficient of the matrix $X(n)$ and can be expressed by the unit delay sampling value of input signal.

In the filtering process, based on the special control algorithm [6, 7], the self-adaptive filter obtains the filter weight coefficients according to the error signal $e(n)$ and the input matrix $X(n)$ and iteratively updates weight coefficient matrix $W(n)$. Through finite iteration, the output signal will approach to the expected signal.

In MWD system, transmitted MWD signal or mud pressure PSK signal are a kind of mechanical modulation signal [8, 9]. Because of mechanical system inertia and pressure signal transmitting in the mud, the carrier wave frequency is limited in the low frequency about a few tens Hertz. The ratio of modulation signal frequency band and carrier wave frequency is usually close to 1 and is a kind of typical broadband signal [10, 11]. Therefore, how to construct the expected signal is a key to get the transmitted MWD signal by self-adaptive filtering. For the mud pressure PSK signals, the signal spectrum is related to data encoding. If the signal average power spectrum is used as the effective feature to construct the expected signal, it is not sufficient to represent all the signals in differential encoding status and only the carrier wave can be used to represent various encoding modulation signal characteristics. However, for the broadband signal, signal frequency in frequency band changes greatly relative to the carrier wave frequency and the encoding information signal cannot be extracted properly if using carrier wave as the expected signal. Therefore, the self-adaptive filter structure and mathematical modeling for processing broadband signal should be adjusted based on the basic mathematical principle of adaptive filter.

### 2.2. The Structure of Self-adaptive Filter

The characteristics change of self-adaptive filter is implemented by adjusting filter weight coefficients with self-adaptive algorithm and all filter weight coefficient adjustment algorithms are trying to make output signal $y(n)$ approach expected signal $d(n)$. The least mean-square error (LMS) algorithm adjusts weight coefficients matrix to make the mean-square value $\varepsilon$ of error signal $e(n)=d(n)-y(n)$ minimize, and when $\varepsilon$ is minimum, the optimal weight coefficient matrix $W^*(n)$ can be obtained to adapt the statistical characteristics of unknown or time-varying signal and noise and the optimal filtering effect will be achieved [12, 13].

Suppose that the discrete downhole signal is the sum of MWD signal $s(n)$ and white Gaussian noise $n_{\mathrm{w}}(n)$. According to the communication theory, the noise introduced in broadband downhole MWD signal is additive random interference and its mean-square value is not zero. When $\varepsilon$ is minimum, it must approach the mean-square value of random noise, and $y(n)$ will approach the MWD signal $s(n)$.

When taking the downhole MWD signal with noise as the expected signal $d(n)=s(n)+n_{\mathrm{w}}(n)$ and carrier wave $x(n)=A_{\mathrm{c}}\sin(\omega_{\mathrm{c}}n)$ as input signal, mud pressure PSK signal $s(n)=A_{\mathrm{s}}\sin\left[\omega_{\mathrm{c}}n-f(n)\right]$ as MWD signal. Among those formulas, $A_{\mathrm{c}}$ is the carrier wave amplitude, $\omega_{\mathrm{c}}=2\pi f_{\mathrm{c}}$ is the angular frequency of carrier wave, $f_{\mathrm{c}}$ is the carrier wave frequency, $A_{\mathrm{s}}$ is the signal amplitude, $f(n)$ is the phase-shift function. Then, the output signal of the self-adaptive filter can be expressed as:

$$y(n)=\sum_{i=0}^{\mathrm{N}-1}w_i(n)x(n-i)=\sum_{i=0}^{\mathrm{N}-1}w_i(n)A_{\mathrm{c}}\sin[\omega_{\mathrm{c}}(n-i)] \tag{3}$$

The mean-square value of error signal can be described as:

$$\varepsilon=E\left[e^2(n)\right]=E\left\{\left[s(n)-y(n)\right]^2\right\}+E\left[n_{\mathrm{w}}^2(n)\right]+2E\left\{n_{\mathrm{w}}(n)\left[s(n)-y(n)\right]\right\} \tag{4}$$

Considering $s(n)$ and $y(n)$ are not respectively relevant with random noise $n_{\mathrm{w}}(n)$, there are $2E\left\{n_{\mathrm{w}}(n)\left[s(n)-y(n)\right]\right\}=0$ and $E\left[n_{\mathrm{w}}^2(n)\right]\neq 0$, then the minimum mean-square value of error signal can be expressed as:

$$\min\varepsilon=\min E\left\{A_{\mathrm{s}}\sin[\omega_{\mathrm{c}}n-f(n)]-\sum_{i=0}^{\mathrm{N}-1}w_i(n)A_{\mathrm{c}}\sin[\omega_{\mathrm{c}}(n-i)]\right\}^2+E\left[n_{\mathrm{w}}^2(n)\right] \tag{5}$$

When $\varepsilon$ approaches the minimum value we can get the result as follows:

$$\sum_{i=0}^{N-1} w_i(n) A_c \sin[\omega_c(n-i)] \to A_s \sin[\omega_c n - f(n)] \quad (6)$$

The physical meaning of Equation (6) is that when the mean-square value of error signal is minimum, the linear sum of the carrier wave value .. at one time and N-1 past time values of $A_c \sin\left[\omega_c(n-i)\right]$ with weight from the weight coefficient matrix can be used to approach the information signal value of $A_s \sin\left[\omega_c n - f(n)\right]$ and realize the reconstruction of mud pressure PSK signal. Where, $N$ is the matrix dimension number or order of the digital filter.

Therefore, the mud pressure PSK signal can be reconstructed by the filter output signal as:

$$y(n) = s(n) = \sum_{i=0}^{N-1} w_i^*(n) A_c \sin[\omega_c(n-i)] \quad (7)$$

Where, $w_i^*(n)$ is matrix coefficient of the optimal weight coefficients matrix $W^*(n)$.

The weight coefficients matrix can be obtained by Widrow-Hoft random gradient algorithm [14] and the matrix coefficients can be expressed as:

$$w(n+1) = w(n) + 2\mu e(n) x(n) \quad (8)$$

When both the conditions of min $\varepsilon$ and $\left.\frac{\partial \varepsilon}{\partial W(n)}\right|_{W(n)=W^*} = 0$ are satisfied, the optimal weight coefficients matrix $W^*(n)$ can be obtained.

In the Equation (8), $\mu$ is the self-adaptive step-size factor which determines the system stability and convergence rate; if $\mu$ is oversize, the convergence rate is higher but the tracking precision of signal will be worse and the system will be divergent when seriously, if $\mu$ is undersize, the convergence rate is unsatisfying and the tracking performance of signal will become worse.

## 3. The Numerical Simulation Analysis of Self-adaptive Filtering Effect

Taking mud pressure PSK signal as the transmitted MWD signal, according to mathematical model of mud pressure DPSK signal and QPSK signal [15, 16], the MWD signal can be expressed as $s(t) = A_s \sin[2\pi f_c - f(t)]$. Among the formula, carrier wave frequency is $f_c = 20\text{Hz}$, signal amplitude is $A_s = 1\text{Pa}$, data code of the DPSK signal is $C_{\text{DPSK}}$=[1 1 1 1 1 1 1 1 1 1], data code of the QPSK signal is $C_{\text{QPSK}}$=[0 0 0 1 1 0 1 1 0 0], both maximum frequencies of the two kinds of coding signal spectrum are $f_{\max} = 30\text{Hz}$, the signal power is $P_s = (A_s/\sqrt{2})^2 = 0.5\text{Pa}^2$; the mean-square value of the introduced white Gaussian noise is $n_w^2(t) = 0.5\text{Pa}^2$, the signal-to-noise ratio is $SNR = P_s / n_w^2(t) = 1$, the order of filter is $\text{K} = 101$, the self-adaptive step-size factor is $\mu = 0.001$, the initial weight coefficient is $w(0) = 0$, the sampling frequency is $f_s = 4000\text{Hz}$. The effect of self-adaptive filter takes the improvement of signal-to-noise ratio (SNR) and the distortion factor of signal waveform as the evaluation criterion. The signal-to-noise ratio of signal can be defined as:

$$SNR = \frac{\sum_{k=1}^{M} \bar{y}^2(k)}{\sum_{k=1}^{M} [y(k) - \bar{y}(k)]^2} \quad (9)$$

The waveform distortion factor of signal can be defined as:

$$D = \frac{\sum_{k=1}^{M}\left[\frac{\bar{y}(k)s(k)_{max}}{\bar{y}(k)_{max}} - s(k)\right]^2}{\sum_{k=1}^{M} s^2(k)} \quad (10)$$

In Equation (9) and Equation (10), $s(k)$ is the mud pressure PSK original signal and $s(k)_{max}$ is its maximum value; $y(k)$ is the output signal of self-adaptive filter; $\bar{y}(k)$ is the output signal of digital low-pass filter after self-adaptive filtering; $\bar{y}(k)_{max}$ is the maximum output signal value of the digital low-pass filter; $k$ is sampling sequence number; $M$ is sampling number in a coding period.

### 3.1. The Numerical Simulation and Analysis of Self-adaptive Filtering on Mud Pressure DPSK Signal

Figure 2 shows the mud pressure DPSK signal without noise, Figure 3 shows the mud pressure DPSK signal mixed with white Gaussian noise with SNR=1 and Figure 4 shows the reconstructed mud pressure DPSK signal waveform after self-adaptive filtering. In Figure 4, the noise in reconstructed signal decreases substantially and SNR is 25.5, raised nearly 25 times. Through frequency spectrum analysis, the noise in reconstructed signal is high-frequency noise outside the frequency band of mud pressure DPSK signal, and can be eliminated by an ordinary digital low-pass filter. Figure 5 shows the signal waveform of reconstructed mud pressure DPSK signal passing a digital low-pass filter with cut-off frequency 40Hz and the noise outside the frequency band is almost eliminated. In Figure 5, the reconstructed signal has some extent of waveform distortion comparing with the original signal in Figure 2 and the distortion factor is about 10.9%. The reason is that the filter step-size factor is too small for improving the ability of tracking noise, which results in lower convergence rate and the increasing reconstruction error of low frequency component in mud pressure DPSK signal frequency spectrum. Increasing the step-size factor will bring down the ability of tracking noise and the SNR of reconstructed signal, but the ability of tracking low frequency component in mud pressure DPSK signal frequency spectrum will be improved and the signal distortion factor will be decreased. Therefore, appropriate increasing the step-size factor can improve the reconstructed signal quality, but the signal distortion factor will raise when the step-size factor reaches the critical value because of higher convergence rate and low tracking accuracy. Table 1 shows the numerical computation. results among the value of step-size factor, the SNR and the distortion factor of the reconstruction signal.

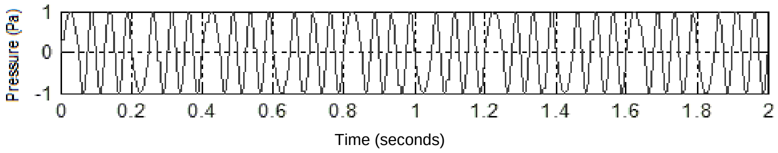


Figure 2. Mud Pressure DPSK Signal Without Noise

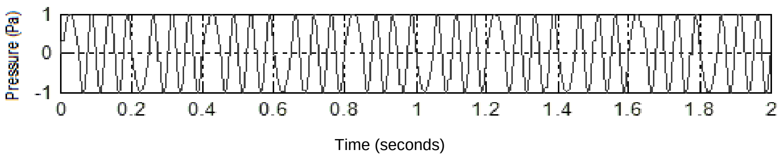


Figure 3. Mud Pressure DPSK Signal Mixed with white Gaussian

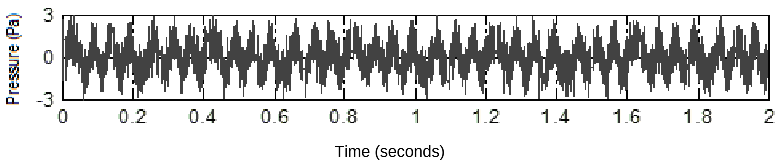


Figure 4. Reconstructed Mud Pressure DPSK Signal after self- adaptive Filtering

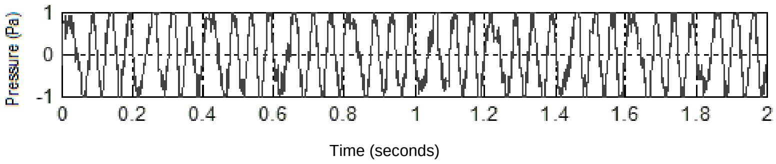


Figure 5. Waveform of the Reconstructed Mud Pressure DPSK Signal

Table 1. Impact of filter step-size factor on reconstructed mud pressure DPSK signal

| Step-size factor | SNR | Distortion factor(%) |
|---|---|---|
| 0.0005 | 67.1 | 14.8 |
| 0.001 | 25.5 | 10.9 |
| 0.002 | 11.4 | 7.1 |
| 0.003 | 6.4 | 6.4 |
| 0.004 | 4.2 | 4.4 |
| 0.005 | 3.1 | 6.6 |

The numerical simulation and filtering effects show that the self-adaptive filter can eliminate the noise in signal frequency band and choosing an appropriate step-size factor can minimize distortion factor of reconstructed signal. Though there are certain noises left in the reconstructed signal, the noises are outside the signal frequency band and can be eliminated by an ordinary digital low-pass filter, then the signal SNR will be improved greatly.

### 3.2 The Numerical Simulation and Analysis of Self-adaptive Filtering on Mud Pressure QPSK Signal

Figure 6 shows the mud pressure QPSK signal without noise, Figure 7 shows the mud pressure QPSK signal mixed with white Gaussian noise with SNR=1 and Figure 8 shows reconstructedmud pressure QPSK signal waveform after self-adaptive filtering.

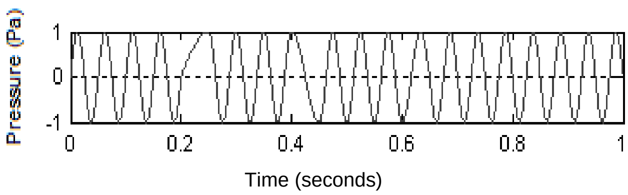


Figure 6. Mud Pressure QPSK Signal without Noise

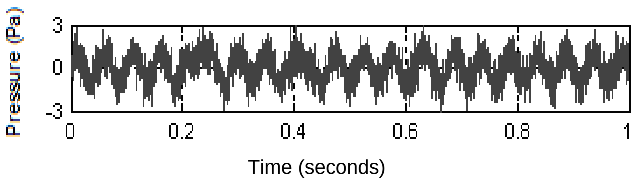


Figure 7. Mud Pressure QPSK Signal Mixed with white Gaussian Noise

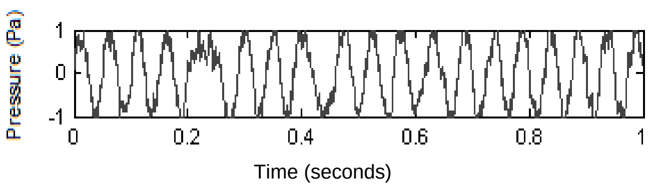


Figure 8. Reconstructed Mud Pressure QPSK Signal after Self-Adaptive Filtering

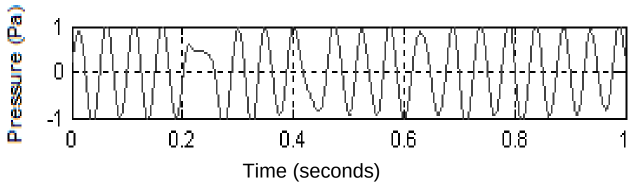


Figure 9. Waveform of the Reconstructed Mud Pressure QPSK Aignal Passing a Digital Low-Pass Filter with 40Hz cut-off Frequency

In Figure 8, the noise in reconstructed signal decreases substantially and SNR is 24.4, raised nearly 23 times. Because of the noise in reconstructed signal being outside the signal frequency band, it can be eliminated by an ordinary digital low-pass filter. Figure 9 shows the signal waveform of reconstructed mud pressure QPSK signal passing a digital low-pass filter with cut-off frequency 40Hz and noise outside the frequency band is almost eliminated. In Figure 9, the distortion factor of reconstructed mud pressure QPSK signal is about 7.3%. Table 2 shows the numerical results among the value of the step-size factor, the SNR and the signal distortion factor. This indicates that the distortion factor of reconstructed mud pressure QPSK signal is generally smaller than that of reconstructed mud pressure DPSK signal and the reconstruction quality of mud pressure QPSK signal after self-adaptive filtering is relatively better than that of mud pressure DPSK signal, but choosing a reasonable step-size factor is the key to get lower signal distortion factor. Because of more complex demodulation of mud pressure QPSK signal than that of mud pressure DPSK signal, the low distortion factor of reconstructed mud pressure QPSK signal provides a good condition for the correct demodulation of the signal.

Table 2. Impact of filter step-size factor on reconstructed mud pressure QPSK signal

| Step-size factor | SNR | Distortion factor(%) |
|---|---|---|
| 0.0005 | 68.9 | 8.8 |
| 0.001 | 24.4 | 7.3 |
| 0.002 | 9.8 | 5.6 |
| 0.003 | 6.7 | 5.6 |
| 0.004 | 4.7 | 4.2 |
| 0.005 | 3.2 | 4.4 |

## 4. Conclusions

Theoretical analysis and numerical simulation show that the self-adaptive filter using transmitted MWD signal mixed with noise as the expected signal and carrier wave as the input signal can realize the noise elimination of broadband signal, which is suitable for eliminating random noise introduced in mud pressure PSK signal in transmission process.

Self-adaptive filter can eliminate the random noise in signal frequency band. The noise in reconstructed signal is outside the signal frequency band and can be eliminated by an ordinary digital low-pass filter, a higher SNR will be obtained.

The quality of reconstructed signal depends on the signal distortion factor being related to the filter step-size factor, therefore the lower signal distortion factor can be obtained by choosing a reasonable filter step-size factor. In addition, numerical calculation shows that the distortion factor of reconstructed mud pressure QPSK signal is smaller than that of the mud pressure DPSK signal under condition of the same filter step-size factor.

**Acknowledgements**

This work was financially supported by the Project of National Natural Science Foundation of China under Grant 51274236 and the Project of High-tech Research and Development Program of China under Grant 2006AA06A101. The authors would like to express their thanks for the sponsoring of publishing this paper.

## References


[1] Hutin R, Tennet RW, Kashikar SV. *New mud pulse telemetry techniques for deep-water applications and improved real-time data capabilities*. SPE/IADC Drilling Conference. Amsterdam, Netherlands. 2001. SPE/IADC 67762: 1-8.

[2] Marsh JL, Fraser EC, Holt AL. *Measurement-while-drilling mud pulse detection process: an investigation of matched filter responses to simulated and real mud pressure pulses*. SPE Symposium on Petroleum Industry Applications of Microcomputers. San Jose, California. 1988. SPE 17787: 1-8.

[3] Brandon TL, Mintchev MP, Tabler H. Adaptive compensation of the mud pump noise in a measurement-while-drilling system. *SPE Journal*. 1999; 4(2): 128-133.

[4] Kuan He, Tao Huang. Adaptive filter design based on Matlab. *Journal of Wuhan University of Technology*. 2008; 30(1): 70-72. (in Chinese)

[5] Chong Zhu, Xiaoming Liang. Performance study of adaptive speech noise canceling based on LMS algorithm. *Journal of Guilin University of Electronic Technology*. 2008; 28(4): 298-301. (in Chinese)

[6] Suisheng Ye, Ronggui Yu, Xiao Wu, etal. The research and application of a new adaptive LMS. *Electrical Measurement & Instrumentation*. 2008; 45(7): 19-22. (in Chinese)

[7] Yan Geng, Duanjin Zhang. Survey of adaptive filtering algorithms. *Information and Electronic Engineering*. 2008; 6(4):315-320. (in Chinese)

[8] Moriarty K A. *Pressure pulse generator for measurement-while-drilling systems which produces high signal strength and exhibits high resistance to jamming*. US6219301 (Patent). 2001.

[9] Malone D. *Sinusoidal pressure pulse generator for measurement while drilling tools*. US4847815 (Patent). 1989.

[10] Yue Shen, Yinao Su, Gensheng Li, etal. Numerical modeling of DPSK pressure signals and their transmission characteristics in mud channels. *Petroleum Science*. 2009; 6(3): 266-270.

[11] Yue S, Yinao S, Gensheng L, etal. Transmission characteristics of DPSK mud pressure signals in a straight well. *Petroleum Science and technology*. 2011; 29(12): 1249-1256.

[12] Yongfang Xie, Hongjun Wu, Yanni Deng, etal. Harmonic detection method based on modified adaptive filter. *Journal of WuHan University of Technology*. 2008; 30(7): 123-126. (in Chinese)

[13] Rong Mei, Shanhua Yao. Adaptive filter applied in adaptive noise canceller system. *Instrumentation Technology*. 2008; 8: 13-15. (in Chinese)

[14] Liye Song, Jingsheng Wang, Jishen Peng. Algorithm Research of Adaptive Filter and DSP Simulation Realization. *Modern Electronics Technique*. 2009; 5: 112-114. (in Chinese)

[15] Yue Shen, Yinao Su, Lin Li, etal. Analysis on transmission characteristics of differential phase shift keying signal of continuous pressure wave in drilling fluid channel. *Acta Petrolei Sinica*. 2009; 30(4): 593-597. (in Chinese)

[16] Yue Shen, Jun Zhu, Yinao Su, etal. Transmission characteristics of the drilling fluid pressure quadrature phase shift keying signal along a directional wellbore. *Acta Petrolei Sinica*. 2011; 32(2): 340-345. (in Chinese)