

Research Article

Delay Pressure Detection Method to Eliminate Pump Pressure Interference on the Downhole Mud Pressure Signals

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The feasibility of applying delay pressure detection method to eliminate mud pump pressure interference on the downhole mud pressure signals is studied. Two pressure sensors mounted on the mud pipe in some distance apart are provided to detect the downhole mud continuous pressure wave signals on the surface according to the delayed time produced by mud pressure wave transmitting between the two sensors. A mathematical model of delay pressure detection is built by analysis of transmission path between mud pump pressure interference and downhole mud pressure signals. Considering pressure signal transmission characteristics of the mud pipe, a mathematical model of ideal low-pass filter for limited frequency band signal is introduced to study the pole frequency impact on the signal reconstruction and the constraints of pressure sensor distance are obtained by pole frequencies analysis. Theoretical calculation and numerical simulation show that the method can effectively eliminate mud pump pressure interference and the downhole mud continuous pressure wave signals can be reconstructed successfully with a significant improvement in signal-to-noise ratio (SNR) in the condition of satisfying the constraints of pressure sensor distance.

1. Introduction

In measurement while drilling (MWD), various downhole signals will be transmitted to the surface in real time for instructing the drilling operation. One of the most common methods of transmitting the measured downhole information to the surface is through mud pressure pulses produced by mechanical modulation of a mud siren in MWD tools and transmitted at acoustic speed in the mud flow. The mud siren generates mud continuous pressure wave signals with complex modulation methods to produce higher data rates. When transmitting the mud pressure signals, there will be a lot of pressure noise and interference, among which the mud pressure fluctuation generated by the mud pump contributes to the largest influence. The mud pump pressure interference is related to the pump stroke rate which includes fundamental component and harmonic component. When the mud pump is in imbalance operation mode caused by sealing problem or in abnormal working status, some higher harmonic amplitude will become very large. Although the

pressure dampers are equipped on mud pump pipe, the pressure fluctuation generated by mud pump reaches or exceeds the downhole signal strength detected in the stand pipe [1]. These higher harmonics will enter the frequency band of mud pressure signal and thereby create great interference that cannot be eliminated by conventional signal processing method, leading to the great decrease of signal-to-noise ratio (SNR) of signal and affecting extraction of the MWD signals. Many studies had been done to eliminate the pump interference. Marsh and others proposed the matched filter method which treated mud pump interference as random noise and calculated the autocorrelation coefficient to eliminate the mud pump pressure interference [2]. However, the pump interference is a kind of system interference rather than random noise, so the conclusions of the method needed further discussion. Brandon and others proposed an adaptive compensation method which uses extracted interference component in the signal and automatically adjusts strength of the interference component to eliminate the pump pressure interference impact on the signal [3], but the effect was

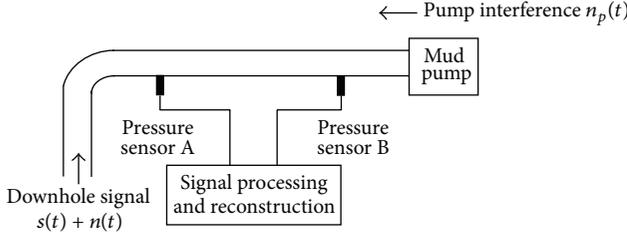


FIGURE 1: Mud pressure detection system.

limited. Some literatures [4–7] introduced the delay pressure detection technique and built a mathematical model, being fitted to the single-frequency signal with pressure sensors distance of quarter signal wavelength, for eliminating the mud pump pressure interference. Because components of many frequencies are contained in mud continuous pressure wave signals, the mathematical model presented in those literatures cannot be applied in reconstruction of actual mud continuous pressure wave signals. Based on transmission path analysis of mud pump pressure interference and downhole mud pressure signals, the authors established the mathematical model in time domain for processing mud continuous pressure wave signals according to the fundamental mathematical principle of delay pressure detection method and then studied the reconstruction method of mud continuous wave signals in both time domain and frequency domain and constraints of the distance between pressure sensors.

2. Mathematical Model of Delay Pressure Detection

The delay pressure detection method uses two pressure sensors being some distance apart on the mud pipe to detect and process the mud pressure signal; Figure 1 shows the schematic figure of mud pressure signal detection system. Two pressure sensors, A and B, having distance L_0 between each other, are equipped in a straight pipe between wellhead and mud pump. The pressure signals received by two sensors contain downhole signal (mud pressure signal) $s(t)$, downhole random noise $n(t)$, and mud pump pressure interference $n_p(t)$. The transmission direction of pump pressure interference is opposite to that of downhole signal. Suppose that the propagation velocity of the mud pressure wave is c_0 and the pressure wave transmission time between sensors A and B is $\tau_0 = L_0/c_0$.

Considering the mud pipe between sensors A and B as a linear system, its frequency response can be described as

$$H(j\omega) = |H(j\omega)| \cdot e^{-j\omega\tau_0}, \quad (1)$$

where $|H(j\omega)|$ is modulus of frequency domain transfer function of the mud pipe between pressure sensors A and B.

Suppose that $h(t)$ is unit impulse response of the linear system $H(j\omega)$. When the signal is being transmitted through

the linear system [8], signals received by the pressure sensors A and B can be expressed as

$$\begin{aligned} p_A(t) &= s(t) + n(t) + h(t) * n_p(t), \\ p_B(t) &= h(t) * [s(t) + n(t)] + n_p(t). \end{aligned} \quad (2)$$

We can get convolution of $h(t)$ with $p_B(t)$ as

$$h(t) * p_B(t) = h(t) * h(t) * [s(t) + n(t)] + h(t) * n_p(t). \quad (3)$$

Equation (3) means that $p_B(t)$ is transmitted through a linear system with unit impulse response $h(t)$ again. Because $h(t)$ contains delayed time $\tau_0 = L/c_0$, the physical meaning of (3) is that $p_B(t)$ will be detected after delayed time τ_0 .

Subtracting the formula in (3) from $p_A(t)$, we can get the delay pressure detecting signal as follows:

$$\begin{aligned} p_A(t) - h(t) * p_B(t) &= s(t) + n(t) \\ &\quad - h(t) * h(t) * [s(t) + n(t)]. \end{aligned} \quad (4)$$

In (4), the pump pressure interference item $n_p(t)$ has been eliminated.

After Fourier transform of the formula in (4), we can get spectral density function of the downhole signal as

$$S(j\omega) + N(j\omega) = H'(j\omega) [P_A(j\omega) - P_B(j\omega) \cdot H(j\omega)], \quad (5)$$

where $H'(j\omega) = 1/(1 - H(j\omega) \cdot H(j\omega))$ can be applied to reconstruct the downhole signal.

3. Signal Reconstruction Based on Time-Domain Differential Equation

According to (5), the time-domain solution of the system frequency response can be described as the reconstruction of the downhole signal after the delay pressure detecting signal $p_A(t) - h(t) * p_B(t)$ is passed through a signal recovering system with frequency transfer function $H'(j\omega)$.

Considering that the maximum frequency of mud continuous pressure wave signal in transmission will be dozens of hertz (Hz), the signal frequency is lower and limited. In limited frequency band, the signal attenuation in amplitude will keep unchangeable when mud continuous pressure wave signal passes the straight pipe between pressure sensors A and B, so the pipe can be seen as an undistorted transmission system and regarded as an ideal low-pass filter. The frequency domain transfer function of the system can be described as

$$H(j\omega) = aG(\omega) e^{-j\omega\tau_0}, \quad (6)$$

where a is the signal attenuation coefficient and $G(\omega)$ is unit gate function with ω_b as unilateral bandwidth. According to the unit impulse response of ideal low-pass filter [9], the unit impulse response of system $H(j\omega)$ can be described as

$$h(t) = \frac{a\omega_b}{\pi} \cdot \frac{\sin[\omega_b(t - \tau_0)]}{\omega_b(t - \tau_0)} = \frac{a\omega_b}{\pi} \text{Sinc}[\omega_b(t - \tau_0)]. \quad (7)$$

After reciprocal transformation of $H'(j\omega)$, we can get

$$H_1(j\omega) = \frac{1}{H'(j\omega)} = \frac{Y_1(j\omega)}{X_1(j\omega)} = 1 - H(j\omega) \cdot H(j\omega). \quad (8)$$

Then

$$Y_1(j\omega) = X_1(j\omega) - H(j\omega) \cdot H(j\omega) \cdot X_1(j\omega). \quad (9)$$

Because transfer functions of $H_1(j\omega)$ and $H'(j\omega)$ are reciprocal, so their input and output functions are inverse of each other.

Substituting input function $x(t)$ and output function $y(t)$ of $H'(j\omega)$ for output function $y_1(t)$ and input function $x_1(t)$ of $H_1(j\omega)$ in (9), there will be

$$x(t) = y(t) - \left(\frac{a\omega_b}{\pi}\right)^2 \text{Sinc}(\omega_b t) * \text{Sinc}(\omega_b t) * y(t - 2\tau_0). \quad (10)$$

Thus, the time-domain solution of the output function of $H'(j\omega)$ can be built as

$$y(t) = x(t) + \left(\frac{a\omega_b}{\pi}\right)^2 \text{Sinc}(\omega_b t) * \text{Sinc}(\omega_b t) * y(t - 2\tau_0), \quad (11)$$

where $x(t)$ is delay pressure detecting signal and can be expressed as $x(t) = p_A(t) - h(t) * p_B(t)$ and $y(t) = s(t) + n(t)$ is reconstructed downhole signal.

Converting the continuous-time system to Z-system of discrete-time and setting $z = e^{j\omega T_s}$, $k = 2\tau_0/T_s$, and $t = NT_s$, we can get the Z-transform of $H'(j\omega)$ as

$$H'(z) = \frac{1}{1 - |H(z)|^2 z^{-k}}, \quad (12)$$

where T_s is the sampling period and N is the number of sample sequences.

According to digital filter theory, $H'(z)$ is a k -order infinite impulse response (IIR) filter system [10] and its frequency domain response, being similar to the low-pass filter with sharp cut-off characteristic, strengthens with k . When $H(z)$ is an ideal low-pass transmission, the output of $H'(z)$ is a differential equation and can be expressed as

$$y(N) = x(N) + \left(\frac{a\omega_b}{\pi}\right)^2 \text{Sinc}(\omega_b N) * \text{Sinc}(\omega_b N) * y(N - k). \quad (13)$$

Equations (13) and (11) have the same structure, so the essence of signal reconstruction process in time domain is to make the delay pressure detecting signal pass through a closed-loop delay feedback system with recursive structure.

4. Signal Reconstruction and Pole Frequency Analysis Based on Inverse Fourier Transform

The straight pipe between pressure sensors A and B will cause pressure signal attenuation. According to the transmission

characteristics of mud pressure wave [11], the attenuation coefficient of pressure signal or the amplitude ratio of mud pipe can be described as

$$a = e^{-L_0/D} \quad (14)$$

with

$$D = \frac{d}{2} \sqrt{\frac{K_l}{\pi f \mu [1 + \psi ((K_l d)/Ee) + \beta_g ((K_l/K_g) - 1) + \beta_s ((K_l/K_s) - 1)]}},$$

$$\psi = \frac{1}{1 + (e/d)} \left[\left(1 - \frac{\sigma}{2}\right) + 2\frac{e}{d} (1 + \sigma) \left(1 + \frac{e}{d}\right) \right], \quad (15)$$

where L_0 is the pipe length between pressure sensors A and B, D is the attenuation index, β_g is the volume fraction of gas in mud, β_s is the volume fraction of solids in mud, K_g is the bulk modulus of gas in mud, K_l is the bulk modulus of liquid in mud, K_s is the bulk modulus of solid in mud, E is the bulk modulus of the mud pipe, d is the internal diameter of the mud pipe, e is the wall thickness of the mud pipe, σ is the Poisson's ratio of the mud pipe, μ is the kinematic viscosity of mud, and f is signal frequency.

Because the mud pipe forms an ideal low-pass filter in the limited band $\omega < \omega_b$, (5) can be transformed into

$$S(j\omega) + N(j\omega) = \frac{[P_A(j\omega) - P_B(j\omega) \cdot H(j\omega)]}{1 - a^2 G^2(\omega) \cdot e^{-j2\omega\tau_0}}. \quad (16)$$

After inverse Fourier transform of (16), we can get the time-domain solution of (16):

$$y(t) = s(t) + n(t)$$

$$= \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{[P_A(j\omega) - P_B(j\omega) \cdot H(j\omega)]}{1 - a^2 G^2(\omega) \cdot e^{-j2\omega\tau_0}} e^{j\omega t} d\omega. \quad (17)$$

Suppose that the mud is water-based mud. The computational conditions are listed as follows [12]: internal diameter of the mud pipe is 108.6 mm, wall thickness of the mud pipe is 9.2 mm, the mud kinematic viscosity is 20 mPa · s, the pipe Poisson's ratio is 0.3, volume fraction of gas in mud is 0.5%, volume fraction of solid in mud is 15%, the mud pipe bulk modulus is 210 GPa, and bulk modulus of water in mud is 2.04 GPa, bulk modulus of solid in mud is 16.2 GPa. If signal frequency of mud continuous pressure wave is $f < f_b = 40$ Hz, when the distance between pressure sensors A and B is less than 18 m, the pressure signal attenuation coefficient will be $a > 0.988$ by numerical calculation. This means that transmission loss of mud pressure wave signal is very small and the attenuation coefficient will be close to 1 when the two sensors are nearer to each other.

When $a = 1$, the transfer function of downhole signal reconstruction system can be expressed as

$$H'(j\omega) \Big|_{\omega < \omega_b} = \frac{1}{1 - G^2(\omega) \cdot e^{-j2\omega\tau_0}}$$

$$= \frac{1}{1 - \cos(2\omega\tau_0) + j \sin(2\omega\tau_0)}. \quad (18)$$

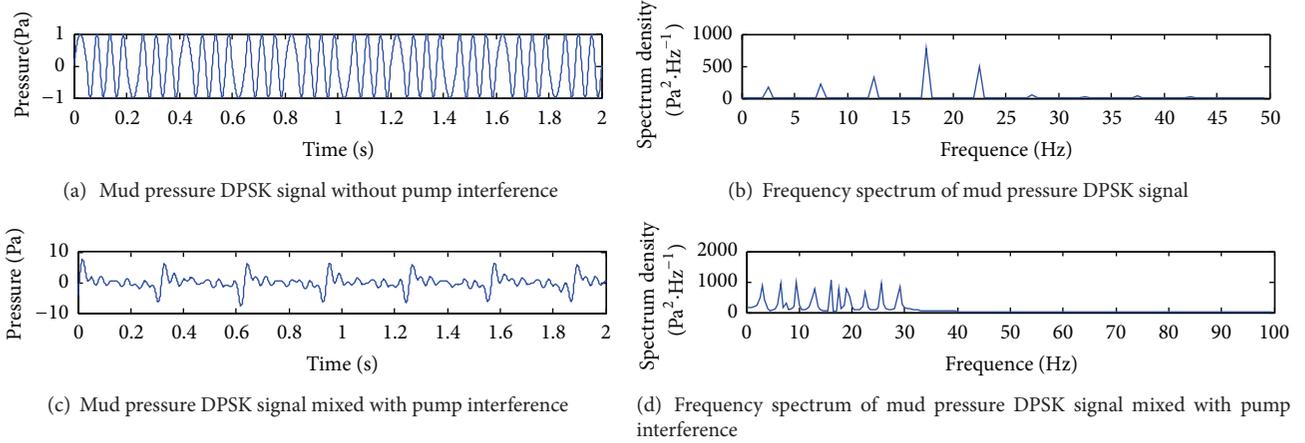


FIGURE 2: Mud pressure DPSK signal mixed with pump interference.

By analyzing (18), there will be generated pole in the condition of $2\omega\tau_0 = 2m\pi$ ($m = 1, 2, 3, \dots$) and the corresponding pole frequency is $f_0 = m/2\tau_0$.

If the maximum frequency of mud pressure signal spectrum is f_{\max} , there is $f_{\max} < f_b$. When the corresponding pole frequency falls into the passband of ideal low-pass filter, the pole frequency will be very likely to enter signal spectrum and generate great interference in the reconstruction of downhole signal. To avoid such situation, all the pole frequency values should be greater than the passband frequency of ideal low-pass filter. That is, $f_0 = m/2\tau_0 > f_b$.

Suppose that $m = 1$ and $\tau_0 < 1/2f_b$; we can get the constraints of distance between pressure sensors:

$$L_0 = \tau_0 c_0 < \frac{c_0}{2f_b}. \quad (19)$$

Propagation velocity of the mud pressure wave in the mud pipe can be calculated according to the literature [13]. Take the mud pressure DPSK (differential phase shift keying) signal with carrier wave frequency of 24 Hz for example, the maximum frequency of signal spectrum is 36 Hz. When $f_b = 40$ Hz, we have $\tau_0 < 1/80$ s. Furthermore, if the mud pressure wave velocity is $c_0 = 1280$ m/s, the corresponding distance between pressure sensors is $L_0 = \tau_0 c_0 < 16$ m.

5. Numerical Simulation of Signal Reconstruction

The numerical simulation takes mud pressure DPSK signal as an example. According to the mathematical model of mud pressure DPSK signal [14], the signal can be formulated as $s(t) = A_c \sin[2\pi f_c t - f(t)]$. In the formula, carrier frequency is $f_c = 20$ Hz, signal amplitude is $A_c = 1$ Pa, and data code is $C = [1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1]$. By analyzing the power spectral of mud pressure DPSK signal, the maximum frequency of signal spectrum is $f_{\max} = 30$ Hz and the signal power is $P_s = (A_c/\sqrt{2})^2 = 0.5 \text{ Pa}^2$. Mud pump interference simulates multifrequency pressure pulsation generated by triplex pump with pump impulse rate 64 r/min, and the fundamental wave frequency is $f_1 = 3 \times 64/60 = 3.2$ Hz with

harmonic orders 2 to 9. Therefore, the frequency changing range of pump interference is from 3.2 Hz to 28.8 Hz. Suppose that the fundamental wave and every harmonic wave amplitude are $A_i = 1$ Pa. The corresponding power density of fundamental wave or every harmonic wave is an impact function $S(f) = (A_i/\sqrt{2})^2 \delta(f - f_i)$ and the average power of the pump interference is

$$\begin{aligned} P_n &= \int_{-\infty}^{+\infty} S(f) df = \int_{-\infty}^{+\infty} \left(\frac{A_i}{\sqrt{2}} \right)^2 \delta(f - f_i) df \\ &= \sum_{i=1}^9 \frac{A_i^2}{2} = 4.52 \text{ Pa}^2. \end{aligned} \quad (20)$$

Therefore, the SNR of signal mixed with the pump interference is $P_s/P_n = 0.11$ when downhole noise is set to $n(t) = 0$.

Figure 2 shows the signal waveform and the signal spectrum mixed with mud pump interference. It can be seen that the mud pressure DPSK signal is completely submerged in the pump interference in time domain and the signal spectrum is completely covered by mud pump interference frequencies.

Suppose that the signal acts on the $H'(j\omega)$ at $t = 0$, $H'(j\omega)$ has zero state response only, and the system output before $t = 0$ is $y(0^-) = 0$. Simulation result of the reconstructed signal by MATLAB programming is shown in Figure 3. It can be seen that the mud pump interference is eliminated after delay pressure detection from Figure 3(a); the reconstructed signal in Figures 3(b) and 3(c) are consistent with the mud pressure DPSK signal in Figure 2(a). In Figure 3(b), the numerical calculation result shows that the SNR of reconstructed mud pressure DPSK signal under condition of $\tau_0 = 3.91$ ms is 72.4, which is about 657 times higher than that of existing pump interference. Numerical calculation and analysis show that the SNR of reconstructed mud pressure DPSK signal will be affected by the delayed time τ_0 in time domain and the influence is listed in Table 1. The reason is that the set value of $y(0^-) = 0$, participating in the recursive computation in (11), will be increased with the delayed time τ_0 ,

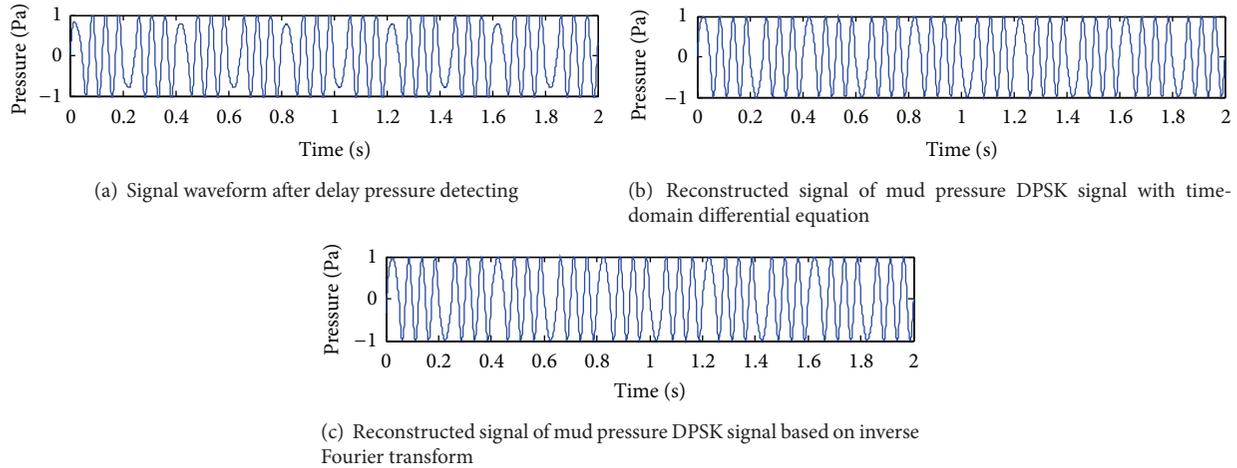


FIGURE 3: Reconstruction of mud pressure DPSK signal.

TABLE 1: SNR of reconstructed mud pressure DPSK signal.

Delayed time τ_0 (ms)	SNR of reconstructed mud pressure DPSK signal
0.98	72.6
1.95	72.6
2.93	72.5
3.91	72.4
4.89	72.1
5.86	70.5

but the influence is not notable. In Figure 3(c), the reconstructed mud pressure DPSK signal based on inverse Fourier transform method has no distortion in whole waveform and is better than the signal reconstructed by time-domain differential equation method in quality. However, both reconstruction methods can reconstruct downhole signal effectively.

Numerical simulation shows that if downhole noise is added to DPSK signal, the reconstructed signals based on the two reconstruction methods are the linear superposition of DPSK signal and downhole noise, which is consistent with theoretical analysis of (11) and (17).

6. Conclusions

(1) Theoretical analysis and numerical simulation show that delay pressure detection method can effectively eliminate mud pump interference and realize reconstruction or recovery of mud continuous pressure wave signals with greater SNR.

(2) To avoid the pole frequency entering into the signals frequency band in signal reconstruction, the distance between pressure sensors should be determined according to the highest signal frequency and the minimum wave velocity.

(3) According to the mathematical principle analysis of delay pressure detection method, it is only applied to eliminate special interference (mud pump pressure interference) whose transmitting direction is opposite to that of the

downhole signal. For mud continuous pressure wave signal which is seriously affected by mud pump interference, this method has some inspiration effect on solving the problem of mud pump pressure interference.

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