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Adaptive dual-sensor noise cancellation method for continuous wave mud pulse telemetry

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ABSTRACT

Mud pulse telemetry is the most commonly used method for transmitting data from downhole to the surface in measurement while drilling (MWD) systems. During the drilling process, the signal received on surface is seriously disturbed by various noise sources, among which the pump noise is the most damaging. The effective cancellation of pump noise is very essential for obtaining correct downhole information and achieving higher data transmission rates. In this paper, an adaptive noise cancellation method using two pressure transducers is studied. The method aims at complex noise environments when two or more mud pumps are used. The fundamental of the method lies on the difference in propagation direction between information signal and pump noise. An adaptive noise cancelling structure is introduced to dynamically estimate the channel characteristics between the two transducers and optimize the noise cancellation output. Both simulations and field experiments were carried out to verify the performance of the proposed method. Simulation results indicate that the method can successfully extract the information signal from pump noise with the interference of random noise from both transducers. Field experiments were carried out during a 3000-meter drilling operation. In the experiment, the major components of pump noise in frequency domain have been reduced by 49%–92%. The successful demodulation of the received data indicates that the proposed method can be used to extract downhole information in complex pump noise environment created by two triplex piston pumps.

1. Introduction

Mud Pulse Telemetry (MPT) systems enable the MWD/LWD companies to transmit to surface valuable directional and formation data during the drilling process (Klotz et al., 2008). In such a system, a controllable valve is installed near the drill bit to generate pressure waves in the mud column by restricting mud flow that passes through. The up-travelling pressure waves will be received by pressure transducers installed on the surface pipeline. The pressure data recorded will be sampled and sent to a decoding unit, where the downhole information will be extracted, demodulated and displayed. It is the most commonly used method for transmitting data from downhole sensors to the surface while drilling (Hutin et al., 2001; Qian et al., 2010).

MPT systems can be generally sorted into three categories according to the type of the pressure wave generated: positive pulse system, negative pulse system and continuous wave system (Hutin et al., 2001; Qian et al., 2010). Continuous wave MPT systems produce pressure waves by changing the relative position of the cross-section of a rotary rotor to the stator (Zhidan et al., 2015). They support complex modulation methods and provide a higher data transmission speed toward the rest. The data transmission speed of the continuous wave MPT system has been reported to exceed 20bps from depths greater than 20, 000 feet (Wasserman et al., 2008). While providing high data rates, the signal strength of continuous wave MPT systems is usually lower than positive pulse types (Wilson et al., 2014a). This causes the continuous wave signal generated to be more sensitive to background noise. Thus, noise cancellation technique has become even more crucial in continuous wave MPT systems.

The downhole information signal received on surface is disturbed by various noise sources, e.g. drill string vibration, bit vibration, turbine, downhole motor, pump noise, etc. Among all noise contributors, pump noise is the most powerful and damaging source for the transmitted mud pulse signal (Stone et al., 1993). Efforts have been made to reduce pump noise at receivers and improve signal-to-noise ratio (SNR). Brandon et al. (1999) reported an adaptive compensation method with two pressure transducers installed on the stand pipe and an isolated mud flow pipe respectively. The pressure detected at the isolated mud flow pipe was used as a reference signal to achieve noise cancellation on the primary

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signal. The performance of such method relies on the low signal-to-noise ratio (SNR) in the reference input. To achieve better performance in nonideal situations, a nonlinear gain method and a signal averaging method is proposed to compress the SNR in the reference signal. Bing et al. (2012) proposed a mud pulse signal recognition method based on clustering algorithm. Normalized Least Mean Square adaptive filter algorithm was used to wipe off pump noise and other interference. Low bit error rate was obtained in the field experiment. Namuq et al. (2013) presented an approach for mud pulse signal detection using continuous Morlet wavelet transformations. In laboratory experiments, hydraulic noise greater than pressure pulse in amplitude was successfully separated. Jing et al. (2017) applied a differential signal extraction method to extract the effective mud pulse signal from pump noise. Two pressure transducers were used. The impulse response of the data transmission between two sensors was evaluated by pump noise before data transmission begins. Based on the difference of propagation direction between the signal and pump noise, the signal was successfully extracted in simulations and laboratory experiments. These researches provide us with novel ways of noise cancellation applicable for different scenes. However, most of the existing literature verified their methods by simulations or laboratory experiments, in which the characteristics of pump noise were relatively simple. Few field test implementation results have been revealed.

The study of this paper aims at a pump noise cancellation method applicable for multiple modulations implemented in complex pump noise environments, e.g. situations that two or more mud pumps must be used. The ranged frequency contents of complex pump noise and various modulation methods together makes the conflicts of information signal and pump noise in frequency domain inevitable. Once the frequency contents of information signal and pump noise overlap, the effectiveness of conventional filtering techniques, e.g. bandpass filters or notch filters will be limited.

To achieve better noise cancelling performance under such circumstance, a differential noise cancellation method using two pressure transducers is used in this study. Comparing with most single-sensor-based methods, such method is more good at dealing with complex or time varying pump noise. The fundamental of the method lies on the difference in propagation directions of information signal and pump noise. By attaching two pressure transducers to the pipeline, two series of pressure data at different locations can be obtained. Each data sequence contains the mixture of up-travelling signals, e.g. the information signal, and down-travelling signals, e.g. the pump noise, with a phase difference caused by transmission delay. The existence of such difference makes it possible to separate information signal from the received signals. Since the information signal and pump noise is separated by the difference in propagation directions, the complexity of pump noise and signal modulation can be, to some extent, ignored.

The implementation of the differential method on noise cancellation has been studied by Wilson et al. (2014b) and Jing et al. (2017). In the existing researches, the propagating characteristics between two pressure transducers were usually assumed to be pre-measured and constant. However, in actual implementation, the complex surface pipeline structure and well site noise makes the accurate estimation of channel characteristics quite difficult. Furthermore, experiment results claim a sign of time-varying feature in the channel characteristics between transducers during the drilling process. Thus, an adaptive feature is imperative for the noise cancellation algorithm to fit the variation in channel characteristics and minimize the estimation errors.

In this study, an adaptive noise cancelling structure (Widrow et al., 1975) is applied to adaptively estimate the channel characteristics between the two pressure transducers. Recursive Least-Squares (RLS) algorithm (Kailath et al., 2000) is used to adjust the weight of the adaptive filter and optimize its output. Details of the algorithm are described in Section 2. With such means, the proposed noise cancellation algorithm shall be able to follow the variation of channel characteristics between transducers. Meanwhile, the self adaptive feature provides the algorithm with minor errors towards single measurement through recursive calculations, which is quiet important in actual implementations.

Simulations and field experiments have been implemented to verify the availability of the proposed method, results and discussions of which can be found in Section 3 and Section 4, respectively.

2. Methods

2.1. Differential noise cancellation using two sensors

Fig. 1 shows the schematic illustration of a MPT system with two pressure transducers installed. In such a system, modulated signal waves are generated by a controllable valve, also known as the transmitter, installed near the drill bit. After been generated, information signal in the form of pressure waves travels upward to surface. Meanwhile, pump noise produced by working mud pumps at the other end of the pipeline is travelling towards downhole, just of the opposite direction. Two pressure transducers, sensor A and sensor B, are attached to the surface pipeline with an appropriate interval. The pressure signals detected by sensor A and sensor B can be viewed as a summation of information signal and pump noise. Due to the difference in propagation direction, a phase difference will appear in both information signal and pump noise at each received signals. Such phase difference sets up the basis of the isolation of two signals.

To describe the differential noise cancellation method mathematically, a more explicit illustration of the mixed signals detected at both sensors is shown in Fig. 2.

In Fig. 2, letters O, A, B and P represent for the location of transmitter, sensor A, sensor B and mud pump(s) respectively. Here we define h_{XY} as the impulse response from point X to point Y, and L_X as the distance from point X to the transmitter. Thus the detected signal at sensor A and sensor B can be described as:

$$Sen_A(t) = h_{0A}*sig(t - L_A/\upsilon) + h_{PB}*h_{BA}*pum(t - (L_P - L_A)/\upsilon) + Z_A(t) \quad (1)$$

$$Sen_B(t) = h_{0A}*h_{AB}*sig(t - L_B/\upsilon) + h_{PB}*pum(t - (L_P - L_B)/\upsilon) + Z_B(t) \quad (2)$$

$Sen_A(t)$ and $Sen_B(t)$ are signals received by sensor A and sensor B at time t respectively. υ is the propagation speed of mud pulses. $sig(t)$ is the signal generated by transmitter at time t. $pum(t)$ is the pump noise generated by mud pumps at time t. $Z_A(t)$ and $Z_B(t)$ correspond to the additive noise at sensor A and sensor B respectively. They are assumed to be independent, identically distributed white Gaussian noises. ($*$) is the operator for convolution.

With Eq. (1) and Eq. (2), the pump noise item $pum(t)$ can be removed by subtraction. To simplify the equation, here we define:

$$g_{AS} = h_{0A}*\delta(t - L_A/\upsilon) \quad (3)$$

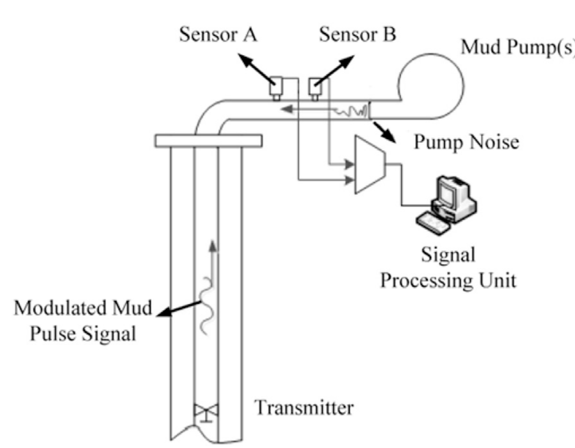

Fig. 1. A schematic illustration of a MPT system with two pressure transducers.