Journal of Theoretical and Applied Information Technology
10th March 2013. Vol. 49 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

WELL FIELD THREE-DIMENSIONAL DRILL STRING VIBRATION SIGNALS' PERIODIC VIBRATION NOISE SEPARATION METHOD RESEARCH

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ABSTRACT

The effect of periodic vibration noise in wellsite is an important factor which impact analysis on three-dimensional drill string vibration signal. In order to obtain more accurate characters of three-dimensional drill string vibration signal that reflects the drilling tools condition, we conduct researches on the periodic vibration noise in the wellsite, independent component analysis algorithm which based on negative entropy for periodic vibration noise signal separation was adopted. At the same time, in order to improve the effect of algorithm demixing, an improved Particle Swarm Optimization algorithm was introduced, combining with periodic noise components which exist in three directions of drill string vibration signals to seek the optimal mixed matrix by which can structure multi-channel mixed-signal of independent component analysis algorithm. This method has high similarity after separation each signal components, in operation has high efficiency. Through the experimental simulation, the method was proven feasible in the drill string vibration periodic noise signal separation.

Keywords: *Drillstring Vibration Signal; Periodic Noise; Independent Component Analysis (ICA); Parameter Optimization*

1. INTRODUCTION

In the drilling process, if we can accurately get information of drilling tools and timely adjust drilling parameters, drilling efficiency would be greatly improved and the life of drill would be extended. Drillstring is the main component of the whole drilling machinery system which is responsible for the drilling. It is considered a highly efficient information channel connect the bottom hole and the ground. Through the analysis of drill string vibration signal can reflect the down hole condition information in time [1]-[2], but most of the drill string vibration signal are collected by piezoelectric acceleration sensor installed on the top drive. Thus inevitably it will be affected by well field noise [3]. If these noise and interference can't be effectively restrained, they will seriously affect the quality of the vibration signal so that the difficulty of recognizing the work condition will be increased. Periodic vibration noise in the drilling site is a common form of wellsite noise. Usually, it is reflected in the form of the measured signal in a fixed frequency signal or in fundamental and each harmonic. They are not easy to be recognized except very few impact cycle signals. For periodic vibration noise, the conventional separation method is to use a notch filter or adaptive filtering [4]. Periodic noise, however, is often not a single frequency. Its fundamental has a certain bandwidth and contains a rich harmonic component. If adopting a single frequency notch filter to process, as soon as it would result in the undesirable effects of the target signal distortion or noise reduction.

Many scholars have made unremitting efforts in the separation of non-single frequency periodic noise. Yang Hongwei and others proposed a method which uses autocorrelation sequence of one way of observed signal to strike a minimum delay of generating the observed signals of the other way [5]. But the experimental results show that the separation effect of the method is not ideal. The algorithm proposed by Wu Xiaopei and others is to extract periodic noise signal from one-dimensional observed signals. In order to construct the noise signal, all its frequency must be accurately estimated. Therefore,

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

requirements of precision are higher for frequency estimation algorithm [6]. For periodic vibration noise of the well field, this paper uses the periodic noise components existed in the drill string vibration signal in three directions, combines the improved particle swarm optimization (PSO) to construct multiple mixed-signal. It solved the not applicable issues of ICA when the number of observed signals is less than the number of sources, and each independent component can be separated from the drill string vibration signal in a very good way.

2. THE PERIODIC VIBRATION NOISE SEPARATION BASED ON ICA

The factors which cause periodic vibration noise in well field is various, such as the cycle pulses stroke of the reciprocating the ground mud pump's, cyclical gear in drillstring system of power transmission equipment, uneven periodic rotation caused by bit failure and periodic vibration when the cone lockup or fold out [7]. These noise sources persist all along in the drilling process. Except the most mechanical Periodic Vibration Noise of the well site, useful periodic noise signals which reflects the drilling conditions is included as well. These periodic noises in the period of time can be regarded as time invariant, stationary additive noise. For the multiplicative noise which exists in actual can be handled after being transformed into additive noise through homomorphic transformation. As the periodic vibration noise and the original three-dimensional drillstring vibration signal are independent of each other, in this paper, ICA could be adopted to separate them.

ICA [8] is a linear mixed-signal separation method of independent signals. Its basic principle can be simply described as: assuming there are n random observation vectors (mixed signals) $\mathrm{x}_1, \mathrm{x}_2, ..., \mathrm{x}_n$, and these vectors can be regarded as a linear combination of the independent signal components $s_1, s_2, ..., s_n$ which are generated by the addition of n independent signal sources:

$$\mathrm{x}_i = a_{i1}s_1 + ... + a_{in}s_n (i = 1, 2, ..., n) \quad (1)$$

In this formula, a_{ij}, $\mathrm{i, j} = 1, 2, \ldots, \mathrm{n}$ are real coefficients. This model assumes that s_i is statistically independent, they can be illustrated as vectors and matrix symbols as follows:

$$X = AS \quad (2)$$

ICA's basic principle is to estimate the mixing matrix A and the independent source matrix S simultaneously only by the observation matrix X in case of the independent source matrix S and the mixing matrix A are unknown. That is, finding a separating matrix W to make S=WX in which W is the inverse matrix of the mixing matrix A.

According to the information theory, Gaussian variables, random variables with unit variance, contain the maximum entropy which can be used to as a Gaussian metric. When measuring the non-Gaussian of during the separating, if the non-Gaussian measure reaches a maximum, it can be concluded that every independent component's separation has been completed. In practical applications, negative entropy is often used to replace the entropy. Negative entropy is defined as follows:

$$J(y) = H(y_{gauss}) - H(y) \quad (3)$$

When the random variable y has a Gaussian distribution, $J(y)$=0 ; When non-Gaussian nature of Y is stronger, the greater the $J(y)$'s value is. Therefore, the negative entropy can be used as metrics to measure the Random variable's non-Gaussian nature. However, the calculation of negative entropy is hard to get, therefore, an approximate formula for the non-Gaussian measure is proposed. If the appropriate $g(y)$ is selected, $J(y)$ can be estimated approximately:

$$J(y) \propto [E\left|g(y)\right| - E\left|g(y_{gauss})\right|]^2 \quad (4)$$

3. THE CONSTRUCTION OF MIXED MULTIPLE SIGNAL

In practical applications, the situation that the number of observed signals is less than the number of sources always occurs. In this case, using the ICA is not appropriate. According to the vibration measurement principle of the acceleration sensor, the measurement of acceleration $a_x(t), a_y(t), a_z(t)$ of arbitrary three-dimensional vibration signal can be expressed as:

$$\vec{a}(t) = a_x(t)\vec{i} + a_y(t)\vec{j} + a_z(t)\vec{z} \quad (5)$$

Journal of Theoretical and Applied Information Technology
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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

The three integrators integrate the vibration acceleration in three directions, forming three-dimensional vibration velocities $v_x(t), v_y(t), v_z(t)$.

$$\vec{v}(t) = \int \vec{a}(t)dt = v_x(t)\vec{i} + v_y(t)\vec{j} + v_z(t)\vec{z} \qquad (6)$$

Discrete three-dimensional signal $P_x(n), P_y(n), P_z(n)$ can be achieved by three-channel synchronous sampling of three-dimensional vibration acceleration or three-dimensional vibration velocity.

$$\vec{P}(n)|_{t=nT} = P_x(n)\vec{i} + P_y(n)\vec{j} + P_z(n)\vec{z},\ 0 \le n \le N-1 \qquad (7)$$

Where T is the sampling period, N is the sampling points. Three-dimensional vibration signal's sampled time domain and frequency domain are analyzed and synthesized. The time domain, as shown in Fig.1, RMS calculating would be done to the direction signal $P_x(n), P_y(n), P_z(n)$ collected.

$$P_{x,y,z} = [\sum_{i=0}^{N-1} P_{x,y,z}^2(i)/N]^{\frac{1}{2}}$$

The total RMS size of the three-dimensional synthetic P and its direction α, β in space are:

$$P = (P_x^2 + P_y^2 + P_z^2)^{\frac{1}{2}} \qquad (8)$$

$$\alpha = arctg(P_y / P_x) \qquad (9)$$

$$\beta = arctg((P_x^2 + P_y^2)^{\frac{1}{2}} / P_z) \qquad (10)$$

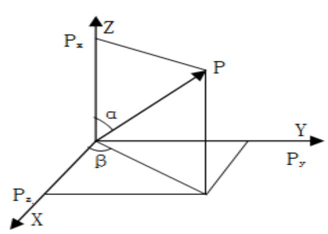

Figure 1. Time Domain Synthesis Of The Three-Dimensional Vibration

The frequency domain, as shown in Fig. 2, FFT spectral analysis is done in the time domain signal collected three directions domain signal $P_x(n), P_y(n), P_z(n)$ respectively:

$$P_{x,y,z}(k) = \sum_{i=0}^{N-1} P_{x,y,z}(n)\exp(-j2\pi kn/N),\ \ 0 \le k \le N-1$$

Three-dimensional spectrum synthesis is done, the size of total energy $|P(k)|$ and direction in space can be obtained and its directions $\alpha(k), \beta(k)$ in space are:

$$|P(k)| = \sqrt{2}(|P_x(k)|^2 + |P_y(k)|^2 + |P_z(k)|^2)^{\frac{1}{2}} / N \qquad (11)$$

$$\alpha(k) = arctg(|P_y(k)| / |P_x(k)|) \qquad (12)$$

$$\beta(k) = arctg((|P_x(k)|^2 + |P_y(k)|^2)^{\frac{1}{2}} / |P_z(k)|) \quad 0 \le k \le N/2 \qquad (13)$$

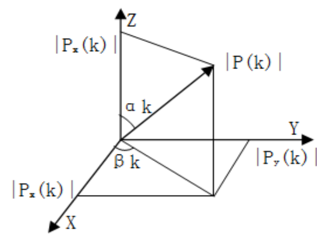

Figure 2. Frequency Domain Synthesis Of The Three-Dimensional Vibration

Time domain synthesis and frequency domain synthesis of the three-dimensional vibration describe the size of the strength or intensity and the direction in space of total three-dimensional vibration of a vibration signal [9].Accordingly, by the acceleration sensor, we can get each periodic vibration noise components in longitudinal, axial and torsional directions, while any dimension vibration noise components is the original noise's projection in this dimension, and that vibration noise on the space decomposition can be regarded as fixed. With these three-dimensional components we can restore the original periodic vibration noise which has complete characterization of the vibration signal characteristics [10]. According to the three-dimensional characteristics of the drill string periodic vibration noise, if two-dimensional vibration signals are selected arbitrarily, the mixed multiple observation signal can be constructed. What every generated multiple observed signal contains full independent component information is a good solution to the problem that the number of observed signals is less than the number of sources. In practice, however, if the mixing matrix A does not select a suitable initial value, the ultimate effect of each component of the solution mixing will be affected. Thus this paper adopted the improved PSO algorithm to

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

optimize the initial value of the mixing matrix A.

The particle swarm algorithm is initialized to a group of random particles by tracking particles itself to find the optimal solution and the entire population to find the optimal solution to update itself, and adopting an iterative method to find the optimal solution. This algorithm's concept is simple and easy to be achieved. There are fewer parameter need to set and the convergence speed is fast. The mathematical expressions of the basic particle swarm algorithm are as follows:

$$v_{ij}(t+1) = wv_{ij}(t) + c_1 r_{1j}(t)(p_{ij}(t) - x_{ij}(t)) + c_2 r_{2j}(t)(p_{ij}(t) - x_{ij}(t)) \quad (14)$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \quad (15)$$

In this formula, w is the inertia weight which controls the previous generation's impact on the next-generation speed; c_1 and c_2 are learning factors; r_1 and r_2 are uniformly distributed random variables in the range [0, 1]; t is iteration number.

Here the author used an improved particle swarm optimization which regarded the projection coefficients of periodic vibration noise in the three-dimensional components as particles and used the periodic noise component which exists in the drill string vibration signals in three directions to seek the optimization of the combination of the signals. This algorithm makes the inertia weight , learning factor linearly decreasing or increasing with the increase of iteration number so that can guarantee the individuals can search the entire space without falling into a local optimum value at the algorithm's initial stage, and at the late stage it can find the global optimum value with the global optimum convergence. In order to avoid the particle's position beyond what is given, the particle boundary conditions should be set to make sure to find optimal solutions in the effective range [11]-[12], thus applied the combination of the mixed multiple signals to the drill string vibrations periodic noise separation.

4. STEPS TO ACHIEVE THE SEPARATION OF DRILL STRING VIBRATION PERIODIC NOISE

(a)Initialize the observed signals: put the any two-dimensional signals of the collected three-dimensional drill string vibration signals into initialization mix, and get three observed signals $x_1(t), x_2(t), x_3(t)$;

(b)Data preprocessing: after demeaning value and whitening process of $x_1(t), x_2(t), x_3(t)$, signal X in which each of the signal components are mutually orthogonal will be obtained.

(c)Iteration: the variable n can be used to indicate the number of iterations. Let $\hat{s}_i^{(n)}$ be a component of $S^{(n)}$ and $w_i(n)$ from separating matrix W (n) be a row of vectors corresponded to $\hat{s}_i^{(n)}$, that is:

$$\hat{s}_i^{(n)} = w_i^T(n) \bullet X; n = 1, 2, 3, ... \quad (16)$$

During the separation process, the results of non-Gaussian are measured by negative entropy's approximate formula. Meanwhile, $w_i(n)$ is adjusted. Algorithm adjustment formula of ICA is:

$$w_i(n+1) = E\{XG'(w_i^T(n)X)\} - E\{G''(w_i^T(n)X)\}w_i(n) \quad (17)$$

(d)Normalize: use $w_i(n) = \frac{w_i(n)}{\|w_i(n)\|}$ to ensure that the separation results have units of energy.

(e)Judge convergence: The adjacent two $w_i(n)$ have no changes or just little change, it can be considered that $\hat{s}_i^{(n)} \approx s_i$ and the iterative process ended.

(f)Parameter optimization: optimize the mixing coefficients of the original target signal in step (a) with improved particle swarm algorithm and repeat step (b) to step (e) until the desired results got achieved or the number of iterations ended. Separation step flow chart is shown in Fig. 3.

5. DRILL STRING VIBRATION PERIODIC NOISE SEPARATION APPLICATION

In order to validate the effectiveness of the method, we have carried on the simulation analysis. Simulation experiment I: the target signals are longitudinal vibration signal and torsional vibration signal $X(t), Xx(t)$ when drill string vibration beating, as shown in Fig. 4. Periodic

Journal of Theoretical and Applied Information Technology
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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

noise is the frequency of 100 Hz sawtooth wave signal $s1$, as shown in Fig. 5 (c). Observation signals are linear superposition of $X(t)+0.8s1$ with $Xx(t)+0.6s1$, as shown in Fig. 5(a) and (b). Above methods are used to separate the periodic noise and two way vibration signals. After the separation, target signals and periodic noise signal as shown in Fig. 5(d) (e) (f).

Simulation experiment II: the target signals are longitudinal vibration signal and torsional vibration signal $X(t), Xx(t)$ when drill string vibration normal drilling, as shown in Fig. 6. Periodic noise is the sine signal $s2$ which is the stack of the frequency of 20 Hz and 32 Hz, as shown in Fig.7 (c). Observation signals are linear superposition of $X(t)+0.8s2$ with $Xx(t)+0.5s2$, as shown in Fig. 7 (a) and (b). Use the above methods to separate the periodic noise and two way vibration signals. After the separation, target signals and periodic noise signal as shown in Fig. 7 (d) (e) (f). With the method in this paper, multiple frequency periodic noise can also be separate, and after the separation, target signals have higher similarity with the previous ones.

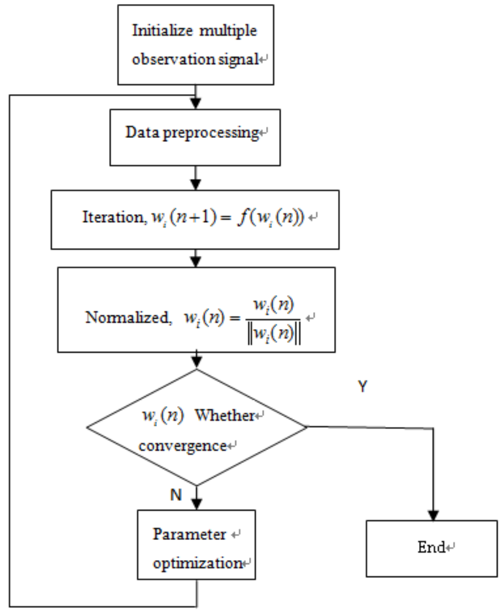

Figure 3. *The noise signal separating flowchart*

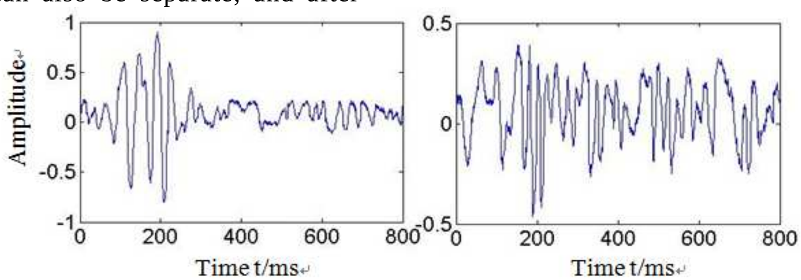

Figure 4. *Longitudinal and torsional vibration signal when drill string beating*

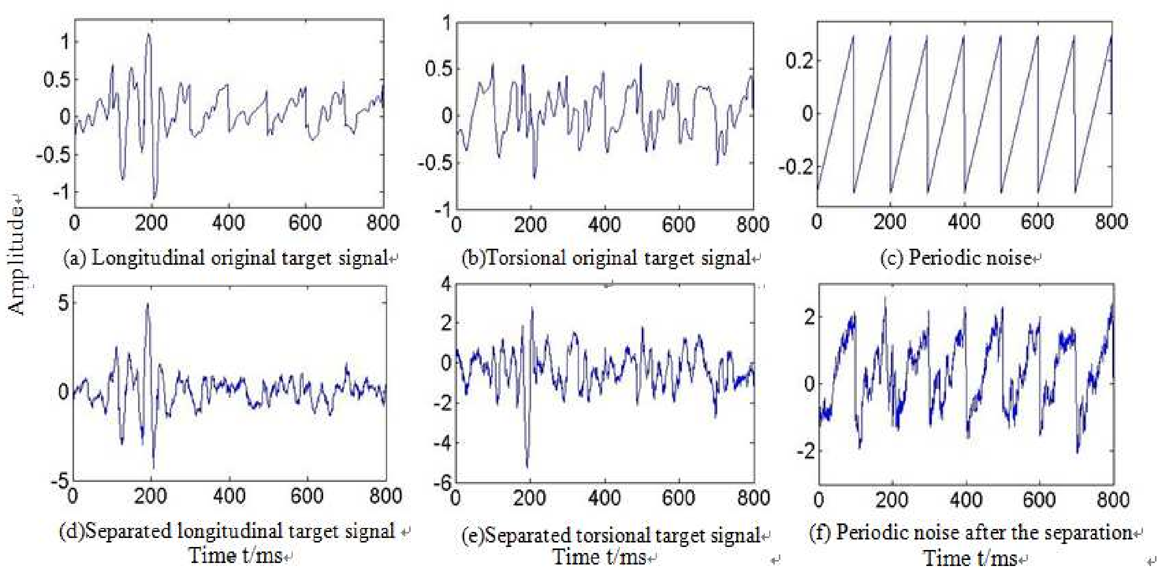

Figure 5. Simulation Experiment I

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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

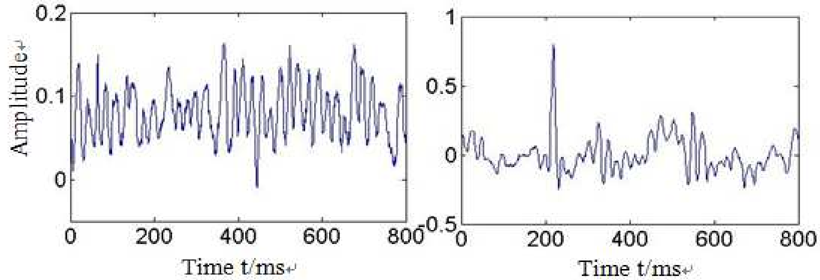

Figure 6. Longitudinal and torsional vibration signalwhen drill string normal drilling

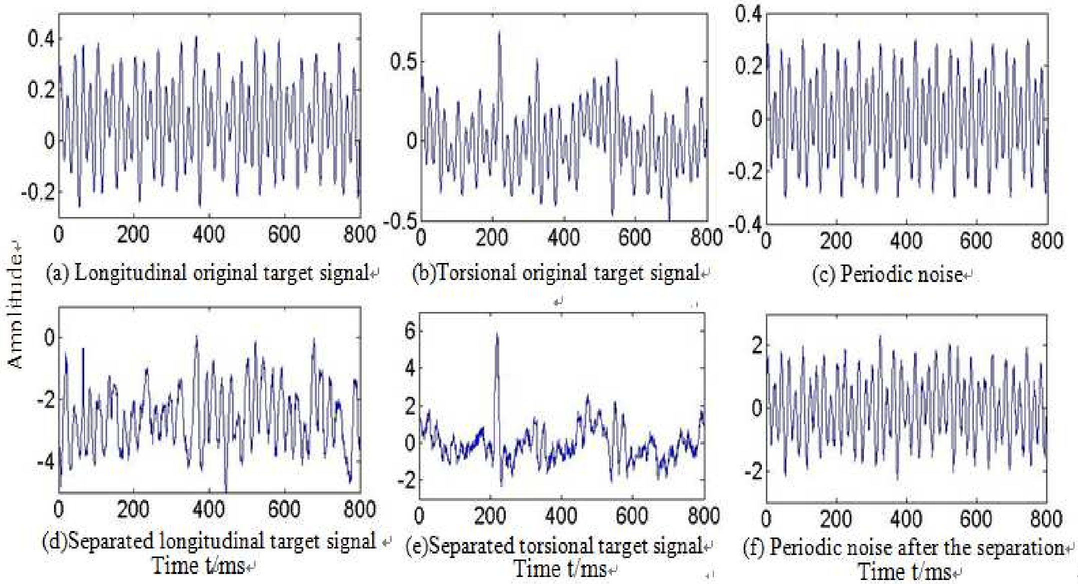

Figure 7. Simulation experiment II

Table 1. Different Signals' Simulation Results

Iteration number	Simulation I Signal Similarity			Simulation II Signal Similarity		
	Longitudinal vibration	torsional vibration	Periodic noise	Longitudinal vibration	torsional vibration	Periodic noise
10	92.32%	91.56%	90.89%	94.68%	95.13%	95.87%
25	94.14%	93.97%	92.37%	96.38%	95.61%	96.11%
48	95.77%	94.41%	93.25%	97.91%	96.17%	96.83%

Table 1 gives the separation of the signals' similarity conditions after the simulation experiment I, II by the above algorithm are presented. The similarity of the signal and the original signal after separation refers to the extent of them adjacent to each other in the Euclidean space. Here the similarity takes a absolute value, the more similar the two signals, the closer similarity coefficient values to 1. From the table we can see that signal similarity improved significantly and tends to be an optimal value with the increase of the number of iteration. In the above figures, we can perceive that separation results are satisfactory. There is applicability of the method in the periodic vibration noise of the drill string vibration signal separation.

6. CONCLUSIONS

In the drilling process, periodic vibration noise will affect the drill string vibration signal persistently. Most of the periodic noise in the well site remains fixed in time and space, and the component of vibration noise of any dimension is the projection of the original noise in this dimension. Make use of periodic noise components present in the three directions of the drill string vibration signal, and combine it with the improved PSO algorithm constructs multiple observed signals to separate the original signal by ICA. Then, verifying the validity of the algorithm separation through simulations.

Due to the uncertainties of the ICA inherent amplitude which results in the amplitude's change before and after the separation of each component so that the amplitude of the signal is required to be restored in the practical application of signal separating. Effective separation of the noise of the drill string vibration signals made more accurate analysis of the useful signal and laid the foundation for the follow-up drill study of drill string vibration signal.

7. ACKNOWLEDGEMENTS

This work was supported by China Petroleum Technology Innovation Fund (2011D- 5006-0308) and China University of Petroleum Graduate student innovation fund (CX-1243).

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