Borehole transient electromagnetic array based relative attitude determination for relief well drilling

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Abstract. Drilling relief well is one of the most effective ways to control blowout well at present. In order to improve the connection rate, the relief well needs to trace a short distance and then gradually approach the accident well, where the relative space attitude determination of relief well and blowout well is the key to improve the drilling efficiency. In this paper, a symmetry multi-coil array based borehole transient electromagnetic (TEM) system for relative attitude determination of relief well drilling is presented. On the basis of the borehole TEM theory, the multi-coil array weighting is applied to improve the detection performance in the case that the blowout well is parallel to the relief well. Moreover, in order to determine the relative attitude, a symmetrical borehole TEM array structure is proposed for the short-range detection. Experiments were conducted and the results demonstrate the effectiveness of the proposed method for improving the short-range detection performance, which would offer significant information for the tracing phase of relief well drilling.

1. Introduction

In the process of offshore and onshore drilling, blowout out and leakage in oil and gas well will not only cause economic losses, but also make serious environmental pollution [1]. Drilling relief well is one of the most effective methods to solve blowout accidents. However, due to the influence of error ellipsoid, it is difficult to hit the target directly only by relying on the trajectory information of relief well and accident well. The relative distance and orientation should be measured continuously in the process of drilling to gradually guide the connection of two wells [2]. Therefore, the location of the blowout well from the relief well is the key to determine the connection [3].

At present, there have been three typical ways for the location of blowout wells, including the geomagnetic disturbance (GMD) method, the current injection method and the transient electromagnetic (TEM) method. Using the measurement-while-drilling’s own fluxgate, the GMD techniques measure the geomagnetic field disturbed by the casing to determine the location of the accident well, where the detection range is limited and the accuracy will be greatly affected by the residual magnetic field of the casing [4,5]. Compared with the GMD detection, the current injection method [6] injects large current into the formation by employing the downhole electrode to form the converging current on the casing of the accident well, which can obtain a larger detection range. The relative distance between the relief well and the blowout well can be obtained by measuring the
magnetic field generated by the converging current \(^{7,9}\). However, this method is too difficult to be implemented due to the high power of the injected current, especially for an offshore drilling. Employing the feature that the resistivity of the metal casing is 6-7 orders lower than that of the formation, the TEM system \(^{10-13}\) determines the relative distance between the relief well and the accident well by detecting the response of the anomaly due to the metal casing in uniform formation \(^{14}\). The above methods have achieved some positive results for measuring the relative position of two wells. However, in the tracing phase with respect to short-range detection, the responses of all three methods contain more information of the metal casing in longitudinal direction, which means the blowout well cannot be regarded as a point target any longer, and will lead to a serious distortion when detecting the distance and orientation. As a result, the relative attitude of the blowout well to relief well cannot be determined accurately, and it is not conducive to the high-precision detection in the tracing phase.

In this paper, we present borehole TEM array based relative attitude determination for relief well drilling. Using a symmetry multi-coil array structure, the response of the casing within the detection range in the accident well is analyzed on the basis of the symmetric characteristics of TEM array and the relative attitude between two wells can be determined. The effectiveness of the proposed method was verified by applying it to experiments and the results show that the short-range detection performance can be effectively improved, which may offer significant information for the tracing phase in relief well drilling.

2. TEM Signal Model for Relief Well

Relief well drilling consists of three stages: approaching, tracing and connecting \(^2\). The design of relief well trajectory should give priority to satisfying the utilization of measurement tool to improve the connection rate. There have been three common trajectories of relief well: gradually approaching, directly connecting and bypass method \(^3,14\), as shown in Figure 1.

Figure 1. Transient electromagnetic (TEM) detection system of relief well

As shown in Fig. 1, the bypass method of relief well C eliminates the error ellipse by approaching the accident well two times. However, if the vertical depth of the connection point for the trajectory cannot meet the requirement of bypass method, the gradually approaching of relief well A should be given priority. At last, if the above two methods cannot be implemented due to the large dogleg, the direct connection method of relief well B can be utilized. The tracing phase of the direct connection
method is suitable for the case that the connection point is very shallow, but the connection rate is lowest. Notably, no matter which kind of the above methods is adopted, the localization of the blowout well in relief well should be made several times in different depths to ensure high connection rate, especially in short-range detection. The detection scheme is shown in red dotted box of Fig. 1. However, long-time tracing will not only be inconvenient for engineering implementation, but also reduce the drilling efficiency of relief well, which is not conducive to minimize the loss of the accident well.

To solve this problem, the borehole TEM array-based short-range detection for relief well including the electrical and geometrical parameters of the jth layer \((\mu_j, \epsilon_j, \sigma_j, \text{and} r_j \text{ with } j = 1,2,\ldots,J)\) are illustrated in Figure 2. We consider the magnetic core to be the innermost layer. The transmitter and the M receivers are located in the second layer, with their number of turns given by \(N_T\) and \(N_R\), respectively, where each receiver has the same number of turns. The inter-element spacing is \(\Delta z\) and the transmitter-receiver distance (TRD) is \(z_m\), \(m=0,1,\ldots,M\), where the receiver with a TRD of zero is collocated with the transmitter.

![Figure 2. TEM detection model of a borehole](image_url)

With the introduction of variables \(x_j\) and \(\lambda\) that satisfy \(x_j^2 = \lambda^2 - k_j^2\) and \(k_j^2=\mu_j\epsilon_j\omega^2-i\mu_j\sigma_j\omega\), the vertical component of the magnetic field in the \(m\)th receiver of multi-coil array with a TRD of \(z_m\) can be obtained by solving the homogeneous and inhomogeneous Helmholtz equations \(^\text{[12]}\)

\[
H_z(\omega, z_m, d_m) = \frac{N_T I_T}{\pi} \int_0^{\infty} x_C(\omega, d_m) I_0(x r) \cos(\lambda z_m)d\lambda
\]

where \(\omega\) denotes the angular frequency, \(I_T\) denotes the transmitter current and \(I_0(\cdot)\) is a modified Bessel function of the first kind of order zero. \(C_i\) denotes the reflection coefficient, which is related to the geometrical and electrical parameters of all the layers. The distances \(d_m\) between the casing of the accident well and the receivers are also included in \(C_i\). Then the induced electromagnetic force (EMF) in the frequency domain of the \(m\)th receiver can then be expressed as
where \( \xi = \mu_j N_r N_t t_v / \pi \) and \( f(\lambda, r, \omega, d_m) = x_1 C(\omega, d_m) |\lambda(x, r)| \). Assuming that the detected area is longitudinally uniform, the distance, shape and other parameters of the anomaly can be obtained by analysing the decay speed of the TEM response. It should be noted that the borehole TEM system is suitable for the multi-cylindrically layered structures and the accident well is actually located on one side of the relief well. Therefore, the \( d_m \) in the TEM signal model in relief well is different from the real distance, where the parameters need to be corrected with gradation. Besides, since the cylindrical symmetry model cannot reflect the azimuth information of the accident well relative to the relief well, it is necessary to obtain it through multiple detection in different vertical depths based on the known well trajectory \([14]\). In this paper, the relative attitude of relief well and blowout well is determined according to the TEM response in the above model.

3. TEM array-based signal processing method for relief well

The traditional relief well detection system uses a single receiving coil for blowout well location. However, when the relative distance between the relief well and the accident well casing is too close, the response of the receiver will contain more longitudinal information of the casing. No matter the relative attitude of the two wells is parallel or oblique, the accident well casing is regarded as a point target, thereby introducing serious measurement error. In this paper, in order to improve the detection performance of the relief well, the multi-coil array-based TEM system with one transmitter and multiple receivers is adopted to detect the metal casing of the accident well several times in different depths.

Given a ramp signal with a turn-off time of \( t_{0i} \), the two integration in Equation (2) can both be expanded as multi-stage Legendre polynomials with respect to the number of stages \( P \) and \( Q \) respectively. Using the Gaver–Stehfest inverse Laplace transform with \( S \) stages, the induced EMF \( U_{m}(t_i, z_m, d_m) \) can be obtained by converting Equation (2) into the time domain, and can be expressed as

\[
U_{m}(t_i, z_m, d_m) = -i \xi \sum_{l=1}^{N_l} \sum_{q=1}^{N_q} \sum_{p=1}^{N_p} g_{s,q,p}(t_i, d_m) \cdot \cos(\lambda_p z_m)
\]

where

\[
g_{s,q,p}(t_i, d_m) = D_s \frac{e^{-\lambda x_{0i}/d_m}}{s} - \frac{A_q}{2} \frac{B_p + 1}{2} f(\lambda_0, 2\pi d_m), \quad \lambda = \pi r^2 \lambda_0 / 2 \]

\( \lambda_0 \) is the upper limit of the infinite integral. In matrix form, Equation (3) can be expressed as

\[
U_{m,t}(t_i, z_m, d_m) = -\frac{\xi}{t_{0i}} \cdot x(z_m) \cdot g^T(t_i, d_m)
\]

where

\[
x(z_m) = \left[ \cos(\lambda_1 z_m), \ldots, \cos(\lambda_p z_m) \ldots \right]_{\lambda_0 \in \lambda}
\]

\[
g(t_i, d_m) = [g_{s,0,p}(t_i, d_m)]_{p=1, \ldots, L}
\]

It can be seen from Equation (5) that the response of TEM system is mainly related to the TRD, the sampling time \( t \) and the relative distance \( d \) between the relief well and the accident well, where the term including TRD \( z \) is a cosine function and can be separated. On the one hand, when the accident well is parallel to the relief well, the geometrical–electrical parameters \( g(t_i, d_m) \) of the multi-cylindrical structure along the borehole axis is the same, and the signals can be weighted according to the array weighting method in Reference [12], so as to improve the signal-to-noise (SNR) ratio and short-range detection resolution.
Assuming that the induced EMFs of each coil are discretely sampled with a sampling length \( L \) and a sampling interval \( \Delta t \), then the induced EMF of the multi-coil array with sampling time \( t_i \) and TRD \( z_m \) can be written as

\[
U_{0,M,1-L} = -\frac{\xi z}{t_0} \begin{bmatrix}
    x(z_0) & g^T(t_1, d_0) & \cdots & x(z_0) & g^T(t_2, d_0) & \cdots & x(z_0) & g^T(t_M, d_0) \\
    x(z_1) & g^T(t_1, d_1) & \cdots & x(z_1) & g^T(t_2, d_1) & \cdots & x(z_1) & g^T(t_M, d_1) \\
    \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\
    x(z_M) & g^T(t_1, d_M) & \cdots & x(z_M) & g^T(t_2, d_M) & \cdots & x(z_M) & g^T(t_M, d_M)
\end{bmatrix}_{(M+1) \times L}
\]

(8)

In (8), if the accident well is parallel to the relief well with \( d_1 = d_2 = \cdots = d_M = d_0 \), a receiving weight vector \( W \) can be applied to optimize the array data of the \( l \)th sampling time \(^12\).

\[
y_l = \frac{\xi z}{t_0} W_{0,M}^T \begin{bmatrix}
    x(z_0) \\
    x(z_1) \\
    \vdots \\
    x(z_M)
\end{bmatrix}
\]

(9)

Using this property, the array weighting can be extended by applying the weight to the received signals of the multi-coil array for all \( L \) sampling times such that

\[
Y_{0,M,l} = [y_1, y_2, \ldots, y_L]
\]

(10)

On the other hand, considering the symmetry of cosine function, the responses of two symmetric receivers with \( z_{z_m} \) should be identical if the distance between the accident well and the relief well is the same. On the contrary, if the signals of the symmetric receivers are not identical, it reveals that the accident well is not parallel to the relief well, and it is necessary to make a further determination on the relative attitude of two wells. Thereby, we can use the response of the symmetric TEM array to determine the relative attitude of two wells by using the symmetric characteristic of cosine function.

4. Symmetric TEM array-based relative attitude determination for relief well

When the blowout well is parallel to the relief well, the relative distance between two wells is the same along the borehole axis; otherwise, it is necessary to determine the relative attitude of two wells according to the responses of the receivers in different observation places. In order to solve this problem, a symmetric TEM array detection method is proposed in this paper. The array structure and the relative attitude of relief well and accident well are shown in Figure 3.

Figure 3. Three attitudes of the relief well and the accident well

The array structure consists of one transmitter and \( 2M+1 \) receivers, where the receiver \( z_0 \) is collocated with the transmitter and the rest \( 2M \) receivers are symmetric with respect to the transmitter (the centre receiver, \( z_0 \)). Since the TRD \( z \) is included in the cosine function, if the distance between the
blowout well and the relief well along the borehole axis is the same, the response of the symmetric element of array should be identical. Then, the relative attitude of two wells can be determined by analysing the response of each element of symmetric array.

Firstly, assuming the threshold $\delta$ and taking $m$ from $-M$ to $M$, if there exists

$$(11)$$

$$Y_{(m), m, l, l} - U_{0, 0, l, l} \leq \delta$$

the weighted array output from $-z_m$ to $z_m$ is nearly the same as the response of a receiver with a TRD of zero, which means the accident well is parallel to the relief well. Conversely, if there is no symmetry of the response of any pair of symmetric receivers, the accident well should be not parallel to the relief well within the detection area. Then, it is necessary to determine whether the accident well is partially parallel to the relief well or not. By dividing the multi-coil array into two parts (termed as the upper part and the lower part) without the centre receiver, and taking $m$ from 1 to $M$ and from -1 to $-M$, respectively, if there exists parallel part, we have

$$(12)$$

$$Y_{1, m, l, l} - U_{0, 0, l, l} \leq \delta \quad \text{or} \quad Y_{2, (-m), 1, l, l} - U_{0, 0, l, l} \leq \delta$$

The parallelism of the two wells correspond to the two parts of the multi-coil array can be analysed from Equation (12), as shown in attitude 2 in Fig. 3(b). On the contrary, if both the upper part and the lower part of the multi-coil array do not satisfy Equation (12), the accident well is completely not parallel to the relief well within the detected area. Assuming that there is no anomaly except the metal casing of the accident well in the formation, the shorter the distance of two wells is, the better the performance of the TEM response can be achieved when the conductivity of the metal casing is a constant. Therefore, the trajectory of the casing in the accident well relative to the relief well can be determined by analysing the response of the $M$ symmetrical receivers one by one. In addition, considering the limitation of the dogleg during drilling, it is impossible to have two inflexion points in accident well in a short distance. In this paper, the responses of the multi-coil array are differential accumulated as $E$ to evaluate improve the SNR and the accuracy of the TEM system for relative attitude determination such that

$$(13)$$

$$E = \sum_{i=1}^{L} \sum_{m=1}^{M} \left( U(t_i, z_m, d_m) - U(t_i, -z_m, d_m) \right)$$

The relative attitude determination process is shown in Figure 4.
5. Experiment and Analysis
In this paper, the standardized 5\(\frac{1}{2}\)-inch metal casings are utilized as the accident well to verify the validity of the TEM array-based relative attitude determination method for relief well drilling. The distance in normal direction of transmitter is used to represent the distance between the accident well and the relief well, and the relative distance of two wells is 3 meters. The relative attitudes of the two wells are shown in Fig. 3, in which the inclination angle of the casing and the relief well in non-parallel area is 15 degrees. The parameters of the multi-coil array sensor and the experiment are shown in Table 1.

| Parameter                                      | Value          |
|------------------------------------------------|----------------|
| Radius of the multi-coil array sensor          | 65 mm          |
| Length of the sensor                           | 1300 mm        |
| Number of transmitting coils                   | 1              |
| Number of receiving coils                       | 9              |
| Number of transmitting coil turns              | 80             |
| Number of receiving coil turns                  | 300            |
| Wire diameter of transmitting coil             | 0.46 mm        |
| Wire diameter of receiving coil                 | 0.18 mm        |

For the convenience of description, the TEM array consists of 9 receivers from \(-z_4\) to \(z_4\). The induced EMFs at 30 ms and 50 ms corresponding to three attitudes of Fig. 3 are shown in Figure 5 and 6.
It can be seen from Fig. 5 and 6 that for both early and late sampling times of 30 ms and 50 ms, respectively, the signal of multi-coil array for attitude 1 shows typical symmetrical characteristic, which indicates that the accident well is completely parallel to the relief well. The signals of the symmetrical receivers are not identical for attitude 2 and 3 in Fig.4. By using the relative attitude determination method in Section 4 and analysing the characteristic of the signal in upper and lower part of multi-coil array, we can conclude that the upper part in accident well is parallel to the relief well whereas the lower part is asymmetric for attitude 2. The accident well is not parallel to the relief well for attitude 3, but the distance of the upper part to relief well is smaller than that of the lower part.

For different attitudes, on the one hand, by analysing the symmetric or asymmetric relationship of the signal of the upper and lower receivers, the determination whether the accident well and the relief well are completely parallel or not can be made; on the other hand, if only the upper part or the lower part of the multi-coil array is considered, the induced EMF will change with different observation places because the distance between each receiver and the accident well casing is not the same.
Therefore, we can determine the partially parallel area through any half signal of the multi-coil symmetrical array.

![Graph showing induced EMF vs sampling time for different receivers.](image)

**Figure 7. Comparison of the symmetrical array signal for attitude 3**

In addition, the incline direction can be obtained by analysing the signal of multi-coil array for attitude 3 in Fig. 4. As shown in Fig. 7, the signal of the upper part in the symmetrical array is significantly larger than that of the lower part, which indicates that the casing of the upper part of the accident well is closer to the relief well. Notably, since the response of each receiver contains more information in longitudinal direction of the accident well, the smaller the element spacing of symmetrical receivers is, the lower resolution of response can be obtained by considering the influence of noise and detection error, and the difference of the response of $\pm z_1$ is significantly less than $\pm z_4$ as shown in Fig. 7. Notably, the array signal processing method proposed in this paper can only calibrate the general attitude, and the accurate calculation method of the relative angle of the accident well and the relief well needs to be investigated further in future studies.

**6. Conclusion**

In this paper, a symmetry TEM array based relative attitude determination for relief well drilling is proposed to improve the detection performance in the short-range tracing phase. Based on the TEM signal model, the array weighting is applied and the symmetrical TEM array structure is employed, where the relative attitude of two wells can be determined by analysing the symmetry of the response of the symmetrical array. The experiment results of three different attitudes demonstrate that the proposed method can effectively determine the relative attitude between the accident well and the relief well, which is of great significance to improve the short-range detection performance and drilling efficiency of the relief well.

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