Eccentric array-based borehole transient electromagnetic system for NDT of multipipe strings in sidetrack well

Yang Ling\textsuperscript{1,a}, Dang Ruirong\textsuperscript{2,b}, Dang Bo\textsuperscript{3,c}, Guo Rui\textsuperscript{4,d}

\textsuperscript{1}Shaanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells Xi’an Shiyou University Xi’an, Shaanxi
\textsuperscript{2}Shaanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells Xi’an Shiyou University Xi’an, Shaanxi
\textsuperscript{3}Shaanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells Xi’an Shiyou University Xi’an, Shaanxi
\textsuperscript{4}Shaanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells Xi’an Shiyou University Xi’an, Shaanxi
\textsuperscript{a}alingyang2915@163.com, \textsuperscript{b}dangrr2648@126.com, \textsuperscript{c}bodang521@126.com, \textsuperscript{d}gr12140@163.com

Abstract. In the middle and late stage of oilfield development, the sidetracking technology is widely used for restoring the production of stripper well, damaged well and abandoned well. In this paper, we present an eccentric array-based borehole transient electromagnetic (TEM) system for nondestructive testing (NDT) of multipipe strings in sidetrack well. Using the borehole TEM signal model, the response of eccentric sensor is analyzed, which contains more information in the direction of eccentricity. On this basis, multiple eccentric sensors with different depths and different angles are utilized to form an eccentric array, which can be used to determine the direction of sidetracking and to detect the multiple pipes in hanging casing strings. The performance of the proposed system was verified by applying it to sidetrack wells in Shengli oilfield. In addition, field experiments were conducted, and the results demonstrated the effectiveness of the proposed method.

1. Introduction

With the development of the oil & gas well, the applications of the sidetrack well in offshore oilfields and onshore oilfields are increasing, where the problems of sidetracking, recovering and drilling are followed [1-3]. On the one hand, when drilling inside the casing, the drilling direction cannot be identified due to the interference of the residual magnetic field of the casing itself, so that the direction can only be determined by the existing tool. Even if the sidetracking is out of the casing, it will still be affected by the magnetic field, which will lead to serious direction error [4-5]. On the other hand, the angle of sidetracking is relatively small in the casing. To drill out the casing, it must go through a large section of hanging. However, the length of the hanging section, the size of the sidetracking and the damage of the multipipe strings are unknown for drilling and well completion. The actual drilling conditions of many wells are quite different from the previous design schemes [6-7]. These problems not only affect the production, but also may destroy the well. Therefore, it is very important to inspect the casing structure in sidetrack well.
Borehole transient electromagnetic (TEM) method, which is also known as transient (pulsed) eddy current testing, has been widely used in nondestructive testing (NDT) of downhole casings [8-10], owing to its rapid measurement over a broad frequency range. However, conventional downhole TEM systems are only suitable for symmetrical cylindrically layered structures; the problem of azimuthal NDT of downhole casings remains to be solved.

In this paper, we present an eccentric array-based borehole transient electromagnetic system for NDT of multipipe strings in sidetrack well. Based on the borehole TEM signal model, we analyzed the response of an eccentric sensor with respect to a distance to the axis. Moreover, by utilizing the multiple time slices of the eccentric-array sensor, the direction of the sidetracking can be determined and the NDT of multipipe strings can be achieved. We verify the performance of the proposed system by applying it to a sidetrack well used for NDT of multipipe strings.

2. Borehole TEM signal model with an eccentric sensor

The borehole TEM system equipped with eccentric transmitting and receiving coils that are wound around a soft magnetic core with their number of turns given by \(N_T\) and \(N_R\), respectively, are illustrated in Fig. 1. The electrical and geometrical parameters of the \(j\)th layer are defined as \((\sigma_j, \epsilon_j, \mu_j)\) and \(r_j\), respectively. Assuming that the eccentric sensor is located a distance \(\rho_0\) away from the borehole axis and that the soft-magnetic-core axis forms an angle \(\phi_0\) with the positive X axis. The coordinates of any point in space can be denoted by \(R=(\rho, \phi, z)\) and \(z\) denotes the distance between the transmitting coil and the receiving coil.

\[
\begin{align*}
\n\end{align*}
\]

Due to the eccentricity of the sensor, the TEM detection model is no longer axisymmetric. Therefore, the current loop of the transmitting coil can be regarded as a magnetic dipole source. Introducing the vector potential \(F\), the current loop (ring area \(S\), transmitting current \(I_T\)) of the transmitting coil can be represented by a magnetic dipole point source with magnetic moment \(m=N_T I_T S\), then the inhomogeneous Helmholtz are given by

\[
\begin{align*}
\n\end{align*}
\]

where \(J_m=i \omega \mu_0 \delta(\mathbf{r})\mathbf{e}_z\) is magnetic flux density, \(k\) is the wavelength, \(\omega\) is the angular frequency and \(\delta(\mathbf{r})\) is the Dirac delta function.

By solving (1) and introducing the variables \(\lambda\) and \(x\) that satisfying \(\lambda^2=k^2-x^2\), the primary magnetic field of the eccentric sensor can be obtained by

\[
\begin{align*}
H_i(\omega, \rho, \phi, \rho_0, \phi_0) = \begin{cases} 
\frac{-im}{8\pi} \sum_{n=-\infty}^{\infty} \int_0^\infty \lambda^2 J_n(\lambda\rho_0) H_n^{(1)}(\lambda\rho) e^{-i\omega x} dx & \rho > \rho_0 \\
\frac{-im}{8\pi} \sum_{n=-\infty}^{\infty} \int_0^\infty \lambda^2 J_n(\lambda\rho_0) J_n(\lambda\rho) e^{-i\omega x} dx & \rho < \rho_0 
\end{cases}
\end{align*}
\]

where \(J_n(\cdot)\) and \(H_n^{(1)}(\cdot)\) denote the first type of modified Bessel function and the second type of Hankel function of order \(n\), respectively. The longitudinal component of the secondary magnetic field
produced by the magnetic dipole source in each layer satisfies the homogeneous Helmholtz equation and the secondary magnetic field in the first layer can be expressed as

$$H_{1d}(\omega, d, \rho_0, \varphi_0, \rho, \varphi) = -\frac{im}{8\pi} \sum_{n=1}^{\infty} \int_{-\infty}^{\infty} e^{i\alpha z} J_\nu(\lambda, \rho_n) e^{-i\omega \rho \lambda} dx$$

(3)

where $d$ denotes the thickness of metal pipe, $\zeta$ is the unknown variable which can be calculated using the boundary condition of each layer. Therefore, the induced electromotive force (EMF) of the eccentric sensor can be written as

$$U(\omega, d, \rho_0, \varphi_0) = -i\omega \mu_0 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H_{1d}(\omega, d, \rho_0, \varphi_0, \rho, \varphi) \rho d \rho d \varphi$$

(4)

where $\varphi_{\text{min}}$ and $\varphi_{\text{max}}$ are the maximum and minimum values of the effective integral angle of the eccentric sensor with respect to the origin $O$, respectively. $h(\varphi)$ and $q(\varphi)$ are the two intersections of any ray from the origin and the receiving coil, which is related to the eccentric angle.

Then, given a ramp signal with a turn-off time of $t_{\text{off}}$, the induced EMF in the time domain can then be obtained by the $P$-stage Gaver–Stehfest inverse Laplace transform method with $i\omega = p \ln 2 / t$ [11]:

$$U(t, d, \rho_0, \varphi_0) = \frac{\ln 2}{t} \sum_{i=1}^{P} D_i \frac{e^{\frac{p \ln 2}{t_s}}}{\left(p \ln 2 / t_s\right)^i} \int_{-\infty}^{\infty} U(p \ln 2 / t_s, t, d, \rho_0, \varphi_0)$$

(5)

where $t$ and $D_p$ denote the observation time and the integral coefficient of the Gaver–Stehfest inverse Laplace transform, respectively. It can be observed from (5) that the induced EMF of the receiving coil is related not only to the sampling time and the thickness, but also to the eccentric distance and eccentric azimuth. As long as the receiving area is constant, the influence of the eccentric azimuth on the TEM response is the same, which indicates that the induced EMF of the eccentric sensor is mainly related to the eccentric distance. Once the eccentric distance changes, the receiving response will also change correspondingly, which contains sensitive data in the eccentric direction, while in the opposite direction, the detection signal will be relatively weak.

3. NDT of multipipe strings for eccentric array-based borehole TEM system

As shown in Section 2, the eccentric sensor can achieve the directional detection in eccentric direction, but in the opposite direction of the sensor, the TEM response is strongly influenced by the eccentric structure, which will influence the accuracy of the downhole casing inspection. In order to acquire the multiple directional sensitive data and compensate for the performance loss due to the eccentric structure simultaneously. We investigate the eccentric array-based borehole TEM system for NDT of multipipe strings in sidetrack well, as shown in Fig. 2.

Considering the small radial dimensions of the wellbore and taking four array elements as examples, the four eccentric sensors (termed as Eccentric sensors A, B, C and D) have to be arranged in longitudinal direction to ensure the signal strength, which is equivalent to dividing 360 degrees around the well into the same four detection areas. The size and the number of turns of the four sensors is exactly the same and the longitudinal distance between the adjacent two eccentric sensor along the borehole axis is $\Delta z$. 
For the single pipe string structure, the induced EMF of the receiving coil is only related to the wall thickness, and the function relationship can be expressed as [12]

$$U = f(t, d_1, \rho_0, \varphi_0)$$  \hspace{1cm} (6)

It can be seen that the response of single sampling time can be used to calculate the wall thickness of single pipe string. For the multipipe string structure, each pipe string will affect the receiving response. Taking the two pipe strings as example, the function relationship between the induced EMF and the wall thicknesses can be obtained by [13]

$$U = g(t, d_1, d_2, \rho_0, \varphi_0)$$  \hspace{1cm} (7)

We can observe that there are two unknown variables $d_1$ and $d_2$ in (7) which corresponds to the thicknesses of two pipe strings. In order to calculate these wall thicknesses, the induced EMF of two sampling times must be combined at least. In addition, the chosen time slices of sampling times should be optimized to further improve the performance of NDT for multipipe strings of the hanging section in sidetrack well. It should be noted that the sidetracking direction can also be determined by analyzing the amplitude of the eccentric array.

4. Simulation and experiment

To verify the detection performance of the proposed borehole TEM system, the eddy-current fields of a centered sensor and an eccentric sensor for multipipe strings are utilized. The simulation results are shown in Fig. 3, where the simulation parameters are set as follows: $r_1=12$ mm, $r_2=17.5$ mm, $r_3=21$ mm, $r_4=68.38$ mm, $r_5=79$ mm, $r_6=110$ mm, $r_7=123.72$ mm, $\rho_0=10$ mm, $\varphi_0=0$, $N_T=38$ mm, $N_R=144$ mm, $I_T=0.5$ A and $t_0=30$ μs.
Comparing the Fig. 3 (a) and (b), we can observe that the centered sensor has the same detection performance for all directions around the well, while the eddy current diffusion of the eccentric sensor mainly occurs in the direction of eccentricity, which can help improve the performance of NDT of multipipe strings in the corresponding direction. However, the eddy current of the eccentric sensor in the opposite direction is weaker than that of centered sensor. In order to compensate for this performance loss, we chose to use multiple sensors at different eccentric angles and different depths to achieve directional detection while improving NDT performance.

Furthermore, the validity of the eccentric-array method for the NDT of multipipe strings was confirmed by field experiments conducted at a sidetrack well in Linpan oil production plant Shengli Oilfield, China. In our experiment, the longitudinal distance between two sensors is 350 mm and the geometric parameters of each layer in the experiment have the same value as the simulation in the above section, where each eccentric sensor is exactly the same. The experiment conditions of the sidetrack well are shown in Fig. 4.

The hanger in Fig. 4 is set from 947.2 to 949 m, the depth of sidetracking is set from 1449.1 to 1452.1 m, and the length of hanging section with respect to two pipe strings is 501 m. The field experiment results of induced EMF of eccentric array from 930 to 980 m (including the hanger and hanging section) and 1430 to 1480 m (including the sidetracking position) are shown in Fig. 5 and Fig. 6, respectively, where Fig. 5(a) and Fig. 6(a) are the original measurement signal and Fig. 5(b) and Fig. 6(b) are the signal after depth correction.
According to Fig. 5 (a) and Fig. 6 (a), there exists a longitudinal (borehole axis) shift in the depth direction, which is caused by the different depths of the multiple eccentric sensors. Obviously, if the receiving data of the four receivers are compensated according to the actual depth value, the resolution of the NDT of multipipe strings will be substantially increased, as shown in Fig. 5 (b) and Fig. 6 (b). Under this condition, the position of hanger, the length of hanging section and the position of sidetracking can be clearly identified. Especially, the positions of collars for two pipe strings in hanging section can be located correctly, where the casing structure in sidetracked section has only one pipe string. Furthermore, by comparing the response of array element and taking the data from 1420 to 1460 m as an example, the direction of sidetracking casing can be obtained, as shown in Fig. 7.

Figure.5 The eccentric array data including hanging section.

Figure.6 The eccentric array data including sidetracking position.

Figure.7 The induced EMF of multiple eccentric sensors at the same sampling time (30ms).
It can be observed from Fig. 7 that the induced EMF curves of eccentric sensor A and C vary greatly, which corresponds to the influence of the original casing structure, while the change of eccentric sensor B and C is the influence of sidetracked casing. In addition, the induced EMF of eccentric sensor A changes earlier than C, indicating that the direction of sidetracking is in the direction of eccentric sensor A.

5. Conclusion
An eccentric array-based borehole TEM system was proposed to detect the multipipe strings in sidetrack well. We illustrated the TEM property of an eccentric sensor, where the results show that more sensitive information at eccentricity angle can be obtained. On this basis, the direction of the sidetracking can be determined and the NDT of the multipipe strings in hanging section can be achieved by employing the eccentric array. Simulation and field experiments for a sidetrack well at the Shengli oilfield demonstrated the effectiveness of the proposed system.

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