Borehole electromagnetic induction system with noise cancelation for casing inspection

Bo Dang, Ling Yang, Ruirong Dang, and Yan Xie
Key Laboratory of Education Ministry for Photoelectric Logging and Detecting of Oil and Gas, Xi’an Shiyou University, Xi’an 710065, Shaanxi, China

Abstract: A borehole electromagnetic induction (EMI) system with noise cancelation for casing inspection is presented. Based on the analysis of the model for received signal in multi-cylindrical borehole structures, we choose to utilize a receive-only channel as the reference to cancel the effect of the background noise, where a registration matrix is used to compensate for the correlation of the non-isolated reference channel. Moreover, the performance of noise cancelation is verified by applying it to an oil borehole EMI system for the inspection of oil-well casings. Field experiments are conducted and the results demonstrate the effectiveness of the proposed method.

Keywords: borehole, electromagnetic induction, casing inspection, noise cancelation, motion measurement

Classification: Electromagnetic theory

References


## 1 Introduction

Borehole electromagnetic (EM) systems have gained much attention over the past several decades owing to their use in a wide range of applications such as mineral and petroleum exploration, geotechnical and environmental investigations, and fundamental studies of stress and petrophysics [1, 2, 3, 4]. The most significant feature of the borehole EM system is its accessibility to targets that enables highly accurate measurements. In general, motion measurements are required to obtain as much wellbore information as possible. However, in this case, the borehole EM induction (EMI) system [5, 6] utilizing induction coils will be greatly influenced by the magnetic background noise (MBN) due to the motion of the sensor. At present, the effects of MBN are typically reduced by decreasing the measurement rate; however, this reduces the device efficiency and leads to increased energy consumption. More importantly, the MBN cannot be eliminated effectively as long as a moving sensor is involved.

The problem of noise cancelation [7, 8, 9] is rather general and has been investigated extensively in various research fields. In Refs. 7 and 8, a reference-based noise cancelation (RNC) method originating from the standpoint of signal processing was proposed for noise cancelation in the signal channel. This type of method has also been introduced in borehole systems [10], where a preferable isolated or shielded reference channel that is free of the valid signal is assumed. However, in practice, it is very difficult to design an absolutely isolated reference channel because of the physical limitations of bad borehole conditions.

In this letter, we present a registration-RNC-based borehole EMI system for the cancelation of the MBN effect for motion measurement. Using the characteristics of the model for the borehole EMI signal, a registration matrix can be employed to compensate for the correlation of the non-isolated reference channel, and thus, the influence of MBN can be canceled effectively. The performance of the proposed system is verified by applying it to an oil borehole EMI system used for the inspection of oil-well casings [11].
2 Borehole EMI system for casing inspection

Consider a borehole EMI system equipped with coaxial multi-turn transmitting and receiving coils wound around a magnetic core in a cylindrically layered medium (magnetic core, air, tool housing, casing, cement and formation, etc.), where the electrical parameters and geometry parameters of the \(j\)th layer are defined as \((\mu_j, \varepsilon_j, \sigma_j)\) and \(r_j\), respectively. For some deep or super deep boreholes, well cementation should be implemented to avoid borehole collapse; thus, in this case, a casing and cement ring will also be present. The multi-cylindrically layered structures of the borehole EMI system discussed in this letter are illustrated in Fig. 1.

We take the magnetic core as the innermost layer. The transmitting and receiving coils are located in the second layer with their number of turns given by \(N_T\) and \(N_R\), respectively. As shown in previous studies, the response of such a borehole EMI system comprises both standing and outgoing waves with reflection and transmission components. It is assumed that for all coils, the diameter is sufficiently small so that the source region contains only the second layer, and the induced electromotive force (EMF) in the receiving coils is only related to the magnetic field in the innermost layer. Introducing the vector potential \(\mathbf{A}\), the homogeneous and inhomogeneous Helmholtz equations are given by

\[
\nabla^2 \mathbf{A}_j + k_j^2 \mathbf{A}_j = 0 \quad j \neq 2
\]

\[
\nabla^2 \mathbf{A}_2 + k_2^2 \mathbf{A}_2 = -\mathbf{J}_e
\]

where \(k_j^2 = \mu_j \varepsilon_j \omega^2 - i \mu_j \sigma_j \omega\) and \(\mathbf{J}_e\) denotes the electrical source. By introducing variables \(x_j\) and \(\lambda_j\) that satisfy \(x_j^2 = \lambda_j^2 - k_j^2\), the vector potential \(\mathbf{A}\) can be calculated by solving the Helmholtz equations, and the desired magnetic field in the innermost layer with radius \(r\) (0 \(\leq r \leq r_1\)) is obtained as [4]

\[
H_d(\omega) = \frac{N_T I_T r_1}{\pi} \int_0^\infty x_1 C_1 I_0(x_1 r) \cos(\lambda_1 z_0) dx_1
\]

where \(I_T\) denotes the transmitting current and \(z_0\) denotes the distance between the receiving and transmitting coils along the borehole axis. \(I_0(\cdot)\) is the first type of
modified Bessel function of order zero. $C_1$ denotes the reflection coefficient of the innermost layer, which is related to the geometry and electronic parameters of all layers and can be calculated using the boundary conditions. The magnetic field $H_d(t)$ can be obtained by converting Eq. (3) into the time domain [12]. However, for motion measurement, the motion of the sensor will cause a slight change of the effective area for the inhomogeneous static magnetic field around the borehole, resulting in MBN that will strongly influence the performance of the proposed system.

To include the effect of the noise, we assume that the total magnetic fields comprises the desired component $H_d(t)$ and the noise component $H_n$:

$$H_t(t) = H_d(t) + H_n$$

where $H_n$ denotes the background magnetic field that is inhomogeneous and static.

In this case, the total induced EMF can be written as

$$U_t = -N_R \frac{\partial \Phi}{\partial t} = -N_R \frac{\partial (\mu_1 H_d(t) S)}{\partial t}$$

$$= -N_R H_d(t) \frac{\partial (\mu_1)}{\partial t} - N_R \mu_1 \frac{\partial (H_d(t))}{\partial t} - N_R \mu_1 \frac{\partial (S)}{\partial t}$$

where $S$ denotes the effective area of the receiving coils and the three terms in Eq. (5) represent the rates of change of magnetic permeability, magnetic field, and the effective area $S$, respectively. Although the area of the receiving coil itself will not change with respect to $H_d$ because the distance between the receiving and transmitting coils is fixed, the motion of the recovering coils will cause a variation of the effective area of the receiving coils for the inhomogeneous background magnetic field $H_n$. Moreover, in our experiment, the magnetic core operates in the linear regime of the B–H curves [4]; thus, the EMF due to the induced changes in magnetic permeability can be ignored. Then, considering the static properties of $H_n$, we have:

$$U_t(t) \approx -N_R \mu_1 \frac{\partial (H_d(t))}{\partial t} - N_R \mu_1 H_n \frac{\partial (S)}{\partial t}$$

where the two terms denote the desired signal $U_d(t)$ and the MBN $U_n(t)$, respectively. In the proposed borehole EMI system, $U_d(t)$ is mainly related to the metal casing thickness and can be used for the parameter interpretation [4] of each layer. Furthermore, as the first three layers are fixed, only a change in the thicknesses of the metal casing and the cement ring can lead to a change in $U_d(t)$. Considering that the conductivity of the cement ring is much smaller than that of the metal casing, the metal casing thickness can be estimated from $U_d(t)$ by ignoring the effect of the cement ring. Nevertheless, it is obvious from Eq. (6) that the desired signal will be corrupted seriously by the MBN due to the motion of the recovering coils.

### 3 Reference channel based noise cancelation

Using the above model for the signal of the borehole EMI system for casing inspection, we showed that the metal casing thickness can be estimated by detecting the EMF in the receiving coils and that the MBN will have a strong influence on the performance of the borehole EMI system. Now, we show how an RNC-based
The measurement tool shown in Fig. 2 comprises sensor and measurement circuits that are fixed in a waterproof tool housing. The sensor comprises transmitting and receiving coils wound around the same magnetic core. The measurement circuits mainly include a DC–DC converter, a transmit waveform generator, an analog to digital converter (ADC), a microcontroller, a multi-stage filter, and amplifier circuits. All data collected from the receivers are sent to the surface system using DC power line communication in real time. In this letter, we use the proposed borehole EMI system as a nondestructive testing application for casing inspection. Furthermore, the reference channel is added in sensor component and has the same number of turns of the receiving coils as the main channel. The data processing for the main and reference channels is conducted in the surface system. Fig. 2 illustrates the downhole structure and measurement process, where A, B, C, and D represent the different metal casing thicknesses.

As shown in Fig. 2, we let the receiver located closer to the transmitter act as the main channel while the other receiver acts as the reference channel. We assume that $U_d$, $U_{d\text{-ref}}$, $U_n$, and $U_{n\text{-ref}}$ are the vector forms of the desired signal and the MBN of main and reference channels, respectively, where all these are discretely sampled with the sample length $L$ and sample interval of 1 ms by a 16-bit ADC. Then, we obtain the total EMF of the main and reference channels as

$$U_t = U_d + U_n$$

$$U_{t\text{-ref}} = U_{d\text{-ref}} + U_{n\text{-ref}}$$

Clearly, the desired signal in the reference channel is correlated to that of the main channel and can be calculated according to the procedure described in section 2. Thus, there must exist a registration matrix $T \in C^{L \times L}$ that satisfies

$$U_{d\text{-ref}} = TU_d$$

Then, the auto-correlation of the received signal in the main channel can be expressed as
\[
R_t = E\{U_t U_t^T\} = E\{(U_d + U_n) \times (U_d + U_n)^T\}
\]

where \(E\{\}\) denotes the mathematical expectation and superscript \(T\) denotes the transpose operation. As the transmit waveform is not correlated to the MBN, we have

\[
R_t = R_d + R_n
\]

with

\[
R_d = E\{U_d \times U_d^T\}
\]

\[
R_n = E\{U_n \times U_n^T\}
\]

where \(R_d\) and \(R_n\) are the signal correlation matrix (SCM) and the noise correlation matrix (NCM) of the main channel, respectively. It is assumed that \(U_n\) follows a Gaussian distribution in order for the NCM to be diagonal. Moreover, we assume that the MBN of both the reference and main channels is independent identically distributed. As the main and reference channels have the same number of turns of the receiving coils, the NCMs of the two channels are also the same. Similarly, using the registration matrix, the auto-correlation of the reference channel can be expressed as

\[
R_{\text{t-ref}} = T R_d T + R_n
\]

Based on the above relationships, NCM can be estimated as follows. By left multiplying Eq. (7) by \(T\), the received signal in the main channel can be rewritten as

\[
T U_t = T U_d + T U_n
\]

The auto-correlation matrix of Eq. (15) is given by

\[
T R_t T^T = T R_d T^T + T R_n T^T
\]

Then, the SCM can be canceled by subtracting the auto-correlation of the two channels to obtain:

\[
R_n - T R_n T^T = X
\]

with

\[
X = R_{\text{t-ref}} - T R_d T^T
\]

As \(R_n\) is a diagonal matrix, the diagonal elements of \(R_n\) can be calculated by solving the following linear equations:

\[
R_n(l,l) = \sum_{n=1}^{L} (R_n(n,n) \times T^2(l,n)) = X(l,l) \quad l = 1, 2, \ldots, L
\]

where \(F(i,j)\) denotes the \((i,j)\)th elements of matrix \(F\) in the \(i\)th row and \(j\)th column. Finally, we can obtain the SCM by canceling the NCM in Eq. (11), where eigenvalue decomposition can be used to estimate the desired signal as [13]

\[
\hat{U}_d = \lambda_{\text{max}} \cdot V_{\text{max}}
\]

where \(\lambda_{\text{max}}\) and \(V_{\text{max}}\) are the largest eigenvalue and the corresponding eigenvector of the estimated SCM.
4 Field experiments

The validity of our noise cancelation procedure is confirmed by field experiments in the Linpan oil production plant of Shengli Oilfield, China. The experiments are conducted in a production oil well, where the residual magnetic field of the metal casing will be the main component of the background magnetic fields. In the tools used in our experiment, the system parameters are set as follows: \( z_0 = 0.3 \) m, \( r_1 = 0.09 \) m, \( r_2 = 0.18 \) m, \( r_3 = 0.24 \) m, \( N_T = 100 \), and \( N_R = 500 \). As shown in Fig. 2, there are two types of casing (7.72 and 9.17 mm). Each casing is connected by a collar with a thickness of approximately 7 mm so that we obtain \( r_5 = 76.85 \) mm or \( r_5 = 69.85 \) mm with or without the collar. Thus, there are a total of four values for \( r_4 \) as well as for the metal casing thickness (marked as Thickness-A: 7.72 mm, Thickness-B: 14.72 mm, Thickness-C: 9.17 mm, and Thickness-D: 16.17 mm).

Figs. 3 and 4 compare the detection performance of the EMF for motion measurements in four cases with different measurement speeds. The first case uses the ideal induced EMF \( U_d(t) \) based on formula (3) in theory and the second case uses the directly measured EMF. The last two cases employ the basic RNC method and the registration based RNC method, respectively. It can be observed that the borehole EMI system does not work well without noise cancelation even when the
The measurement speed is as low as 300 m/h. The detection performance can be improved effectively using RNC to cancel the effect of the MBN. However, the basic RNC method still results in a performance loss relative to the ideal case because of the cancelation of the effective signal. In contrast, the performance of the registration-based RNC using the reference channel can closely approach the ideal case.

Examination of Figs. 3 and 4 shows that the metal casing thickness is related to the EMFs in the receiving coils. As, unfortunately, a closed form for the calculation of the metal casing thickness from $U_d(t)$ does not exist, the thickness must be deduced using $U_d(t)$. In Fig. 5, we illustrate the theoretical relationship between some of the time slices of $U_d(t)$ and the metal casing thickness (ideal case). The thickness increases monotonically at the EMF amplitude in the receiving coils for all the time slices. Therefore, the inverse interpretation method of [14] can be employed, where the theoretical model of the time slice of $U_d(t)$ in the receiving coils is used as the basis for the calibration of the thickness. The optimal choice of the time slice for the optimal inversion performance is not the key point of this letter and thus the details pertaining to it are not given. In the following performance analyses, we choose the 20 ms time slice as an example in order to demonstrate the effectiveness of the proposed method.

Fig. 6 shows the inversed casing thickness for motion measurement with the speed of 600 m/h, where the EMF values of the last three cases presented in Figs. 3 and 4 are used. The metal casing thickness is calibrated using the time slice at 20 ms shown in Fig. 5. From Fig. 6, using the directly measured data for the motion measurement, we find that the borehole EMI system for the casing inspection is in bad condition. Although the collars can be distinguished using the basic RNC method, it is still difficult to identify the small casing thickness differences. Meanwhile, the second curve that uses our method shows higher resolution for the casing thickness and will provide a more accurate method for casing damage detection.
5 Conclusion

A novel borehole EMI system with noise cancelation is proposed to cancel the effect of MBN for motion measurement. It is shown that the desired signal can be accurately estimated by canceling the noise correlation matrix in the main channel using the registration-RNC based borehole EMI system. Field experiments for oil borehole casing inspection in the Shengli Oilfield demonstrate the effectiveness of the proposed system.

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