A novel coplanar system with a minimal anisotropic effect

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Abstract. To obtain the response of the novel coplanar system, we use an analytic method to solve horizontal component of electromagnetic field in the anisotropic stratigraphic model by introducing the magnetic Hertz vector and the magnetic Hertz scalar from Maxwell equations. This paper examines anisotropic response characteristics between novel coplanar system and traditional coplanar system. The negative response area of the proposed coplanar system is decreased. Compared this with traditional coplanar system, the anisotropic effects have the same trend; the affected amplitude of novel coplanar system is far less than that of the traditional coplanar system. The results of experiments demonstrate the superiority of the proposed coplanar system.

1. Introduction
With the development of fine oil and gas exploration, the obviously electrical anisotropic reservoirs, such as conglomerate formation, thin layer, caving and fracturing types, have become an important exploration direction. At the same time, it is urgent resource to be developed for enhancing or stabilizing well productivity at late period of high water cut stage. The conventional measurement techniques and interpretation theories are based on isotropic assumptions of formation conductivity. It is easy to miss such reservoirs so that much energy is wasted. The tri-axial array induction logging is an effective method to measure the conductivity of sandstone and mudstone and can obtain the horizontal and vertical resistivity. However, the response of coplanar coil system has entirely different characteristics from that of coaxial coil system; the response of coplanar coil system is often more complex and more sensitive to the change in drilling liquid conductivity, invasion zones conductivity, formation conductivity, and formation anisotropy. These parameters may even cause sign flip in the response under many conditions, thereby causing negative response at the bed boundary and seriously nonlinear. Zhang et al. studied the multi-component induction logging’s response in dipping well anisotropic model, which shows that the cross-components are influenced by the dipping anisotropy\textsuperscript{[1]}. Wei et al. and Ertan Peksen used different ways to obtain analytical expressions in cylindrically stratified anisotropic media respectively, which shows the same response of coplanar system may be produced by entirely different formation conductivities in isotropic or anisotropic formations\textsuperscript{[2][3]}. These will become much complicated to interpret or process the measured data. The present paper relates to a new coplanar subarray configuration, which consists of two transmitters and one receiver coil\textsuperscript{[4]}. To obtain the response of the novel coplanar system, we use an analytic method to solve horizontal component of electromagnetic field in the anisotropic stratigraphic model by introducing the magnetic Hertz vector and the magnetic Hertz scalar from Maxwell equations. Meanwhile, we
identify and analyse the advantages of the novel coplanar system in its ability to reduce an anisotropic effect.

2. Anisotropy of the novel Coplanar EMI systems

The novel coplanar coil system adopts a configuration shown in Figure 1, which consists of two transmitters and one receiver coil. The overall coplanar system also consists of 8 subarrays, but all of subarrays share one receiver coil [5]. Table 1 lists parameters for each subarray. Consider a borehole electromagnetic induction system equipped with transverse coil located on the origin, the transverse coil can be equivalent to a magnetic dipole source $M$ because its radius is much smaller than its distance from the receiver coil when an alternating current passes through it during induction logging [6]. Figure 2 shows a transverse magnetic dipole on the origin with conductivity of the horizontal and vertical denoted by $\sigma_h$ and $\sigma_v$ respectively.

![Figure 1. Configurations of a novel coplanar array.](image1)

![Figure 2. Horizontal magnetic dipole on the borehole axis.](image2)

| Subarray | Primary transmitter L/m | Primary transmitter Turns | Secondary transmitter L/m | Secondary transmitter Turns |
|----------|-------------------------|---------------------------|---------------------------|---------------------------|
| 1        | 0.1500                  | 50                        | 0.0750                    | 50                        |
| 2        | 0.2250                  | 62                        | 0.1125                    | 62                        |
| 3        | 0.3000                  | 74                        | 0.1500                    | 74                        |
| 4        | 0.3750                  | 40                        | 0.1875                    | 40                        |
| 5        | 0.5250                  | 34                        | 0.2625                    | 34                        |
| 6        | 0.6750                  | 80                        | 0.3375                    | 80                        |
| 7        | 0.9750                  | 124                       | 0.4875                    | 124                       |
| 8        | 1.8000                  | 124                       | 0.9000                    | 124                       |

The electrical anisotropy means the different conductivity of the formation in different directions, including horizontal resistivity in the horizontal direction (its reciprocal is the horizontal conductivity $\sigma_h$) and vertical resistivity (its reciprocal is the horizontal conductivity $\sigma_v$) in the vertical direction [7]. It is proved in the published classical literature that the magnetic moment consisting of a Hertz vector of a dipole emitter has the form of $M = (M_x, M_y, M_z)^{[8]}$. Its magnetic strength is a time-harmonic field generated by a transmitting coil with a magnetic moment $M$. Neglecting the influence of other interfering factors and supposing the formation is homogeneous, infinite and anisotropic, the conductivity tensor can be expressed as [9]

$$
\sigma = \begin{bmatrix}
\sigma_v & 0 & 0 \\
0 & \sigma_v & 0 \\
0 & 0 & \sigma_h
\end{bmatrix}
$$

(1)

The magnetic moment of the horizontal Hertz vectors are [10]
The Hertz vector of horizontal magnetic dipole can be expressed as\[3\]

\[M_x = M \quad M_y = M_z = 0 \quad (2)\]

The Hertz vector of horizontal magnetic dipole can be expressed as\[3\]

\[\Pi_x = \frac{M}{4\pi} \frac{e^{ik_s \chi}}{\lambda s} \quad \Pi_y = 0 \quad (3)\]

\[\Pi_z = \frac{M}{4\pi} \frac{x}{\rho^2} \left( \frac{\lambda z}{s} e^{ik_s \chi} - \frac{z}{r} e^{ik_r \chi} \right)\]

The Hertz scalar of horizontal magnetic dipole is\[11\]

\[\Phi_x = \frac{M}{4\pi} \frac{ik_s x}{\rho^2} \left[ e^{ik_s \chi} - e^{ik_r \chi} + \frac{\rho^2}{r^2} \left( 1 - \frac{1}{ik_r \rho} \right) e^{ik_r \chi} \right] \quad (4)\]

where \(\rho = \sqrt{x^2 + y^2}\), \(s = \sqrt{\rho^2 + \lambda^2 z^2}\), \(\lambda^2 = \frac{\sigma_h}{\sigma_y}\), \(r = \sqrt{\rho^2 + z^2}\), \(k_h^2 = i\omega \mu \sigma_h\), \(k_v^2 = i\omega \mu \sigma_v\), \(\mu = 4\pi \times 10^{-7}\) H/m.

From Maxwell' equation, we know\[12\]

\[H = i\mu_0 \sigma_h \Pi_m + \nabla \Phi \quad (5)\]

Substitute equation (3) into equation (5), the equation (6) is obtained

\[
\begin{bmatrix}
H_{xx} \\
H_{xy} \\
H_{xz}
\end{bmatrix} = \begin{bmatrix}
i\mu_0 \sigma_h \Pi_{xx} \\
i\mu_0 \sigma_h \Pi_{xy} \\
i\mu_0 \sigma_h \Pi_{xz}
\end{bmatrix} + \begin{bmatrix}
\frac{\partial \Phi_x}{\partial x} \\
\frac{\partial \Phi_x}{\partial y} \\
\frac{\partial \Phi_x}{\partial z}
\end{bmatrix}
\]

Through proper simplification, the following equations are obtained

\[H_{xx} = \frac{e^{ik_s \chi}}{4\pi} \left[ \frac{i\mu_0 \sigma_h}{\lambda s} + \frac{ik_s x - k_h^2 x^2 - 2ik_r x^2}{s \rho^2} \right] \quad (7)\]

\[H_{xy} = \frac{e^{ik_s \chi} xy}{4\pi \rho^2} \left[ \frac{-k_h^2 k_r}{s} - \frac{2ik_r}{\rho^2} \right] - \frac{e^{ik_r \chi}}{4\pi} \left[ \frac{k_h^2}{r^2} - \frac{2ik_r}{r^4} + \frac{k_h^2}{r^4} + \frac{3ik_h^2 x^2 - 3x^2}{r^5} \right] \quad (8)\]

\[H_{xz} = \frac{xe^{ik_r \chi}}{4\pi \rho^3} \left[ k_h^2 + \frac{3ik_h}{r} - \frac{3}{r^2} \right] \quad (9)\]

The induced electromotive force in the receiver is obtained by applying Faraday's electromagnetic induction law.

\[V = i\omega \mu (N^r A^r H_{Tx1r} + N^r A^r H_{Ty2r}) \quad (10)\]

After calibration, we get the formation apparent conductivity\[13\]

\[\sigma_a = \frac{V - V_m}{K} \quad (11)\]

where \(V_m\) is the direct coupled electromotive force, \(K\) is instrument constant.
3. Results and discussion

The response characteristics are investigated when the horizontal resistivity is 4.0 S/m ($\sigma_h = \frac{1}{R_h} = 0.25S/m$) and the anisotropic coefficients are 1.0, 1.2, 1.5, 2, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 respectively. Figure 3 and Figure 4 are the vertical conductivity influence for the two coplanar systems when horizontal conductivity is fixed and the instrument inclination angle are 0°, 90° respectively.

The apparent conductivity of each subarray increases with the increase of the vertical conductivity for the two coplanar systems when formation horizontal conductivity is fixed and the instrument inclination angle is 0°, especially the short array is apparent. The influence of anisotropy coefficient on the novel coplanar coil system is the same as that of the traditional coplanar coil system. However, the affected amplitude is slightly smaller than that of traditional coplanar coil systems. The influence of anisotropy on both coplanar systems is weakened when formation horizontal conductivity is fixed and the instrument inclination angle is 90°. The influence of anisotropy decreases when the conductivity is high. It's not affected by anisotropy when $\sigma_v = 0.1S/m$, 0.2S/m for the traditional coplanar system and the novel coplanar system. The longest subarray 8 of the traditional coplanar system almost unaffected by the anisotropy coefficient because of instrument rod and shield coil.

![Figure 3: Vertical conductivity influence for the traditional coplanar system when formation horizontal conductivity is fixed.](image)

![Figure 4: Vertical conductivity influence for the novel coplanar system when formation horizontal conductivity is fixed.](image)

The response characteristics are investigated when the vertical resistivity is 4.0 S/m ($\sigma_v = \frac{1}{R_v} = 0.25S/m$) and the anisotropic coefficients are 1.0, 1.2, 1.5, 2, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 respectively. Figure 5 and Figure 6 are the horizontal conductivity influence for the two coplanar systems when vertical conductivity is fixed and the instrument inclination angle are 0°, 90° respectively.
Figure 5 and Figure 6 show comparison of apparent conductivity for the two coplanar systems. Note that the coplanar systems are still affected by the horizontal conductivity. It is found that there are eddy currents along the vertical direction and a new horizontal direction by decomposition of coplanar transmitting coil vortex. Only the apparent conductivity of subarray 1 increases with the increase of horizontal conductivity and the remaining subarrays are reduced nonlinearly for the traditional coplanar system. However, the long arrays (subarray 5, 6, 7 and 8) of the novel coplanar system show a trend toward reduction. Comparing with the traditional coplanar system, the apparent conductivity of the novel coplanar system is higher than that of the traditional coplanar system. The influence of horizontal conductivity is less than that of traditional coplanar coil systems for long arrays.

The apparent conductivity increases nonlinearly with the increase of the horizontal conductivity. It also shows a nonlinear decreasing trend affected by skin effect for long arrays, even there exist negative values for the subarray 8 of the traditional coplanar system. However, the apparent conductivity of each subarray increases for the novel coplanar coil system, there is no decreasing and the anisotropy is linear.

(a) Instrument inclination is 0°.  
(b) Instrument inclination is 90°.  
Figure 5 Horizontal conductivity influence for the traditional coplanar system when formation vertical conductivity is fixed.

(a) Instrument inclination is 0°.  
(b) Instrument inclination is 90°.  
Figure 6 Horizontal conductivity influence for the novel coplanar system when formation vertical conductivity is fixed.

4. Conclusions
The response characteristics between the novel coplanar system and the traditional coplanar system generally show the same trend, which are affected by both horizontal conductivity and vertical conductivity. The different influence of subarrays also relates to their spacing. Compared with the traditional coplanar system, the effect of the novel coplanar system decreases with anisotropy in vertical well; and there is no negative response in the horizontal well. Simulation experiments demonstrate the superiority of the novel coplanar system.
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