

**RESONANCE ANALYSIS OF CIRCULAR DIPOLE ARRAY ANTENNA
IN CYLINDRICALLY LAYERED MEDIA FOR DIRECTIONAL BOREHOLE RADAR**

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1. Introduction

Borehole radar is one of the ground penetrating radar (GPR) techniques [1]-[3]. In the borehole radar, radar operates in a borehole, and they can detect some targets such as fractures and geological layers. Most conventional borehole radar system uses dipole antennas, which are omnidirectional. Recently, 3-D estimation of target positions becomes important. For the measurement, we proposed the circular dipole array antenna with an optical modulator [3], as directional borehole radar. The basic idea to estimate direction of arrival wave (DOA) with dipole antenna array is to make use of difference in phase and amplitude of received signals by the antennas.

It is well known that mutual coupling among circular array antenna elements causes phase-sequence resonance [4]-[8]. This resonance is sometimes made use of in some antennas such as a supergain antenna having a large number of elements and electrically large size [8]. On the other hand, the element number and the antenna size is small in the proposed dipole array antenna for the borehole radar in [3]. However, even if in this condition, the phase-sequence resonance may occur. This resonance might influence estimation of DOA with the proposed method in [3]. Especially, if the MoM model did not agree to experimental data, we would fail in direction finding. In this paper, we investigate influence of the phase-sequence resonance of the array antenna on direction finding.

2. Formulation

A. The MoM solution

MoM analysis for the dipole array antenna in a borehole was given in [3], and we briefly review that here. In the analysis, a borehole filled with some fluid was approximated by infinitely long multiple dielectric cylinders. Consider the circular dipole antenna array in the layers shown in Fig. 1 (or see Fig. 7 in [3]). The M vertical dipole antennas are arranged uniformly on a circle at $\rho = b$ and $\phi = \phi_k = \frac{2(k-1)\pi}{M}$ ($k = 1, 2, \dots, M$). We utilize Richmond's MoM, which use Galerkin's method and piece-wise sinusoidal functions. We should notice that we need to calculate the modified Green's function in [2]-[3], since the function should include scattered waves from the cylindrical boundaries. The diameter of all the dipole antennas is $2a$, and is small enough for the thin wire approximation to be applied. In [3], we assumed that a plane wave is incident on the array antenna with the azimuth angle $\phi = \varphi$, and the electromagnetic field can be represented as (17) in [3], or as

$$\begin{bmatrix} E_z^{inc}(\phi, z; \theta, \varphi) \\ H_z^{inc}(\phi, z; \theta, \varphi) \end{bmatrix} = \sum_{n=-\infty}^{\infty} e^{-jk_z z} e^{-jn(\phi-\varphi)} J_n(k_{1\rho} \rho) \mathbf{a}_1^{(n)}. \tag{1}$$

It should be noted that the incident wave can be broken down to into cylindrical harmonic with different $e^{-jn\phi}$ dependence.

B. Circular array resonance

When the resonance having order m ($0 \leq m \leq M/2$) occurs, the voltage V_k at the feeding point of the k -th circular array antenna element in MoM has the form [4]-[8] like

$$V_k = e^{-jm\phi_k} V_0, \quad (2)$$

where V_0 is a complex value, which is independent of ϕ_k . In order to satisfy (2), electric field and magnetic field should be the following form instead of (1).

$$\begin{bmatrix} E_z^{inc}(\phi, z; \theta, \varphi) \\ H_z^{inc}(\phi, z; \theta, \varphi) \end{bmatrix} = \begin{cases} \sum_{l=-\infty}^{+\infty} e^{-jk_z z} e^{-jn(\phi-\varphi)} J_n(k_{i\rho} \rho) \mathbf{a}_1^{(n)} \Big|_{n=m+1N} & (m=0), \\ e^{-jk_z z} J_n(k_{i\rho} \rho) \sum_{l=-\infty}^{+\infty} (e^{-jn(\phi-\varphi)} \mathbf{a}_1^{(n)} \Big|_{n=m+1N} + e^{-jn(\phi-\varphi)} \mathbf{a}_1^{(n)} \Big|_{n=-m+1N}) & (m \neq 0) \end{cases} \quad (3)$$

It should be noted that (3) is the m -th azimuth dependency component extracted from the total plane wave incidence field in (1). If the antenna was excited by the incident field in (3) at the resonance frequencies corresponding to the order m , the current at feeding point of the antennas would be large.

Using parameters: layer number $N = 2$, $\varepsilon_{r1}=1$, $\sigma_1 = 0$, $\varepsilon_{r2}=10$, $\sigma_2 = 0.001$ S/m, $2a_1 = 0.1$ m, antenna element diameter $2a = 1$ mm, circular array diameter $2b = 0.07$ m, antenna full length $l = 1.5$ m, element number $M = 7$, terminated impedance $Z_j' = 1$ pF, we calculated voltage at the feeding point of the antenna located at $\phi = \phi_1 = 0$ with the TM wave incidence. The calculated voltages are broken or dotted lines in figure 2. The red solid line is response by the total field shown in (1), and the four dotted lines correspond to response by the fields in (3). According to the peak positions of the three dotted lines for $m = 0, 1$ and 2 in the figure, we find that the circular array in a borehole is resonated at 70 MHz, 120 MHz and 135 MHz, which correspond to phase-sequence factor $m = 0, 1$ and 2 , respectively. Around the three frequencies, we can see that the received signal excited by the total field has maximum values. These imply that the phase-sequence resonance occur around the three frequencies.

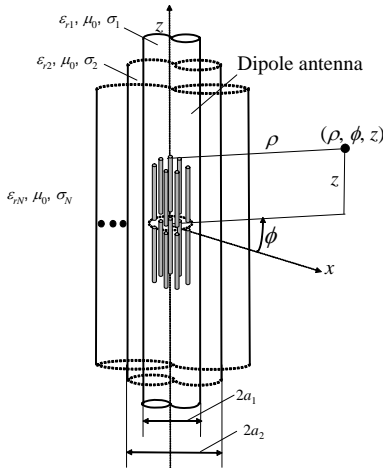


Fig. 1. MoM model.

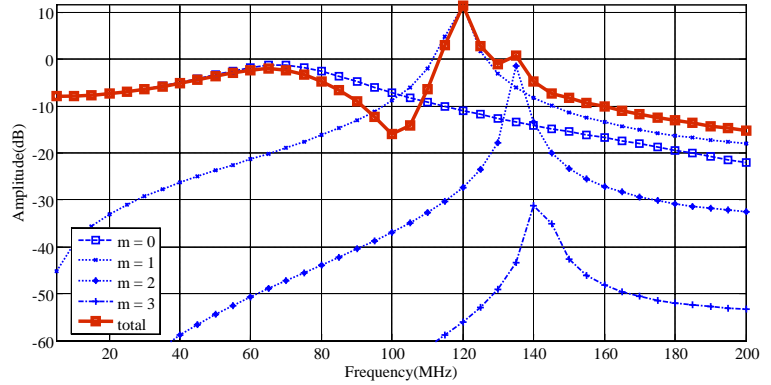


Fig. 2. The calculated voltage at a feeding point of the dipole antenna 1.

3. Influence of phase-sequence resonances on direction finding

A. Phase-sequence resonance analysis of the circular array

Form of the incident field in (1) implies that the received signals V_k can be represented by the linear combination of the M phase-sequence voltage as

$$V_k = \sum_{n=0}^{M-1} e^{-jn(\frac{2(k-1)\pi}{M} - \varphi)} A_n, \quad (4)$$

where A_n is a complex value. Inverse digital Fourier transform of the received signals may extract the m -th phase-sequence component from the received array signals V_k . Since both the order m and $M-m$ represent the same m -th phase sequence resonance, we will evaluate the resonance with the following value ζ_m :

$$\zeta_m = \frac{1}{M} \sqrt{\left(\sum_{k=0}^{M-1} v_k e^{j\frac{2\pi km}{M}}\right)^2 + \left(\sum_{k=0}^{M-1} v_k e^{j\frac{2\pi k(M-m)}{M}}\right)^2} = \sqrt{A_m^2 + A_{M-m}^2}, \quad (0 \leq m \leq M/2) \quad (5)$$

Note that the value ζ_m is the function of a frequency. We can calculate the power ζ_m corresponding to the m -th phase-sequence with the equation (5). Fig. 3 (a) shows the calculated value ζ_m with the theoretical signals generated by the MoM model in Fig. 1. A color scale in the figure corresponds to the value ζ_m . At around 120 MHz and 135 MHz, the power have the high value at $m = 1$ and $m = 2$, respectively. These frequencies correspond to the resonant frequencies of $m = 1$ and 2, which were evaluated in Fig. 2. We should notice that the diameter $2b = 0.07$ m is much smaller than wave length, which is 0.63 m $= (3 \times 10^8 \text{ m/s}) / (\sqrt{10} \times 150 \text{ MHz})$ at 150 MHz. This leads to little phase difference among the antenna elements. If there was no mutual coupling among the antennas, the value ζ_m should be highest at $m = 0$. That is the reason why the power is highest at $m = 0$ below 60 MHz.

B. Analysis of experimental data

We arranged the dipole array antenna in the borehole, BR2, at the field test site of O.E.C.U., Shijonawate, Japan, as shown in Fig. 4. The antenna consists of seven dipole antennas uniformly arranged on a circle, *i.e.* $M = 7$. The parameters of the antennas such as a diameter of this circle and length of the antennas are the same as ones used in the section 2. Fig. 3 (b) shows the value ζ_m , which were calculated with the experimental data. We can see that the power ζ_m is highest at $m = 1$ and 115 MHz. Also, the value ζ_m is high at $m = 2$ and 130 MHz. We can see some similarity between Fig. 3 (a) and Fig. 3 (b), and this implies that the phase-sequence resonance corresponding to $m = 2$ and 3 occurs in the experiment actually.

Fig. 3 (c) shows the averaged coherence among the array signals, and Fig. 3 (d) shows the estimated direction of arrival. We formed a steering vector with the MoM, and estimated the direction with a Fourier-based method using the steering vector. Below 60 MHz in the figure, the estimated direction is correct. However, we can see some spurious solutions between 110 MHz and 120 MHz, or around 135 MHz. These might be caused by the phase-sequence resonance having order $m = 2$ and 3. Also, the estimated direction is biased around 80 MHz, and this frequency is near the frequency of the phase-sequence having $m = 0$ in Fig. 2. It should be noted that there is some error in direction finding, when the phase-sequence resonance happens. In higher frequencies than 180 MHz, inhomogeneous medium around the borehole might cause the error.

4. Conclusions

Using the MoM model including influence of the borehole, we investigated frequency of the phase-sequence resonance in a circular dipole array antenna in a borehole. We applied the inverse digital Fourier transform to both the experimental and theoretical data, and we found that the phase-sequence resonance corresponding order $m = 1$ and 2 occur in the experiment data. Comparison between the resonance analysis and estimation of direction of arrival showed that the phase-sequence resonance increases error in direction finding with a dipole array in a borehole.

Acknowledgements

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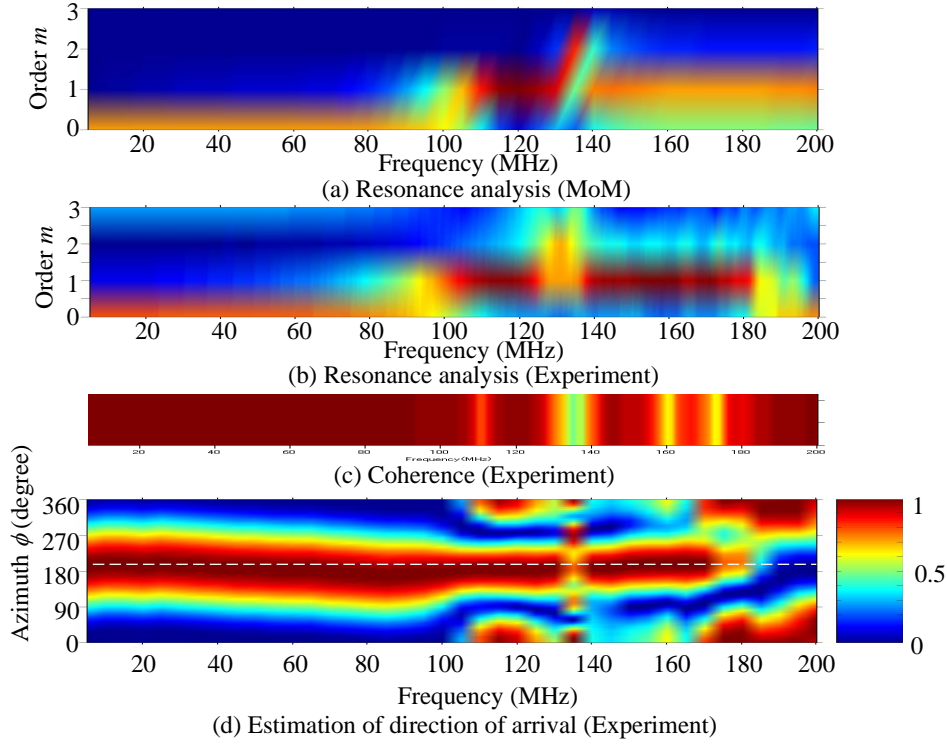


Fig. 3. Analysis results. In (a), (b) and (d), the values are normalized by the maximum one at each frequency. In (d), the white broken line represents the true direction of arrival, which is $\phi = 197^\circ$.

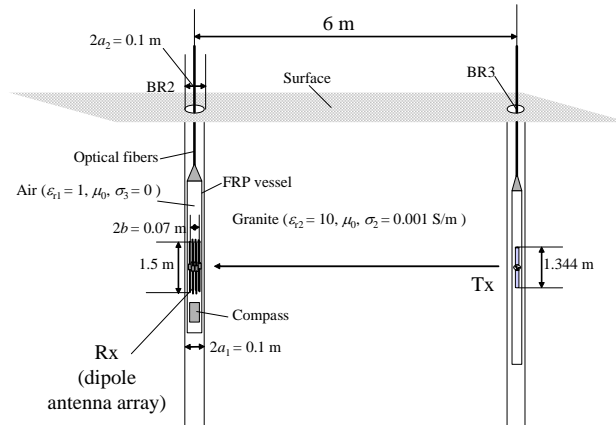


Fig. 4. Experiment to transmit a wave to the dipole array in granite from outside the borehole in O.E.C.U., Shijonawate, Japan.

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