Researches on Sheathed Dipole Antennas and Radio Propagation in Seawater

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***Abstract*— In this paper, input impedance and received power of sheathed dipole antenna is studied by theoretical analysis and the calculation time is greatly shortened compared to full-wave analysis. The transmission line theory is used to discuss the input impedance behavior of the full sheath and half sheath dipole antennas, and formulas of the input impedance are obtained. In addition, a new method is proposed to estimate received power by using full-wave analysis and theoretical analysis effectively. Calculation time for large scale models is greatly reduced.**

Keywords— Terms —theoretical analysis, sheathed dipole antenna, input impedance, propagation loss, received power, calculation time

I. Introduction

The use of electromagnetic waves for communications in the seawater has been studied for many years and it is desired the antenna structure to obtain high received power. In the previous study [1], the sheathed dipole antenna was proposed and the transmission factor between transmitting and receiving antennas was evaluated by the full-wave numerical analysis. However, the calculation time increases greatly when the distance between the two antennas increases by using numerical full-wave analysis.

In this paper, the structure of full-sheath and half sheath dipole antenna is studied by the theoretical analysis. The input impedance behavior and propagation loss of the antenna are discussed. The results of an approximated expression of the input impedance in the case of half sheath dipole antenna is derived. Besides, a new method is proposed to estimate received power by using full-wave analysis and theoretical analysis effectively. Calculation time for large scale models is greatly reduced.

I.Theoretical analysis of sheathed antenna

A. *Structure of half sheathed dipole antenna*

Figure 1 shows the structure of half sheath dipole antenna with PVC-cover in the seawater. a and b represent the radius of the conducting wire and the sheath, respectively. While c is outer radius of the PVC-cover. $2L$ is the total length of the conducting wire and $2l$ is the length of sheath. Region 1 is the sheath of the antenna which contains pure water, with the relative permittivity and the conductivity of ε_{r1} and σ_1, respectively. Region 2 is PVC-cover with the relative permittivity and the conductivity of ε_{r2} and σ_2, respectively. Region 3 is seawater with the relative permittivity and the conductivity of ε_{r3} and σ_3, respectively. k_L is the wave number along the z direction. k_1, k_2 and k_3 are the wave numbers of the region 1, region 2 and region 3, respectively.

B. *Analysis by transmission line theory*

In this structure, both the relative permittivity of region 1 and region 3 are 80 (ε_{r1}=ε_{r3}=80). When the conductivity σ_1 is sufficiently smaller than the conductivity σ_3, the relation $|k_1|<<|k_3|$ can be satisfied. When the outside medium is highly conducting at the operating frequency, the insulated antenna is essentially a coaxial line with a very extensive imperfect outer conductor in which the electromagnetic field is that associated with the volume density of free-charge current through the constitutive relation $J=\sigma E$ [2]. Conventional transmission-line theory is applicable. For the TM01 mode electromagnetic components, the formulas of electromagnetic field in cylindrical coordinate system are given as follow:

Region 1 (pure water $a<r<b$),

$$H_{\phi 1} = \frac{j\omega\varepsilon_1}{k_{r1}}[AJ_1(k_{r1}r) + BN_1(k_{r1}r)]e^{j(\omega t - kz)} \tag{1}$$

$$E_{z1} = [AJ_0(k_{r1}r) + BN_0(k_{r1}r)]e^{j(\omega t - kz)} \tag{2}$$

$$E_{r1} = \frac{jB}{k_{r1}}[AJ_1(k_{r1}r) + BN_1(k_{r1}r)]e^{j(\omega t - kz)} \tag{3}$$

Region 2 (PVC-cover $b<r<c$),

$$H_{\phi 2} = \frac{j\omega\varepsilon_2}{k_{r2}}[CJ_1(k_{r2}r) + DN_1(k_{r2}r)]e^{j(\omega t - kz)} \tag{4}$$

$$E_{z2} = [CJ_0(k_{r2}r) + DN_0(k_{r2}r)]e^{j(\omega t - kz)} \tag{5}$$

$$E_{r2} = \frac{jD}{k_{r2}}[CJ_1(k_{r2}r) + DN_1(k_{r2}r)]e^{j(\omega t - kz)} \tag{6}$$

Region 3 (seawater $r>c$),

$$H_{\phi 3} = \frac{j\omega\varepsilon_3}{k_{r3}}EH_1^{(1)}(k_{r3}r)e^{j(\omega t - kz)} \tag{7}$$

$$E_{z3} = EH_1^{(1)}(k_{r3}r)e^{j(\omega t - kz)} \tag{8}$$

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$$E_{r3}=\frac{jD}{k_{r3}}EH_0^{(1)}(k_{r3}r)e^{j(\omega t-kz)} \quad (9)$$

where,

$$k_{r1}^2= k_1^2- k_L^2, \quad (10)$$
$$k_{r2}^2= k_2^2- k_L^2, \quad (11)$$
$$k_{r3}^2= k_3^2- k_L^2. \quad (12)$$

J_0 and J_1 are the 0th- and1st-order of the Bessel functions, respectively. N_0 and N_1 are the 0th- and1st-order of the Neumann function, respectively. $H_0^{(1)}$ and $H_1^{(1)}$ are the 0th- and1st-order of the first kind Hankel functions, respectively. k_{r1}, k_{r2} and k_{r3} are wave numbers in radial direction in the region 1,2 and 3. The wave number along z direction, k_L can be represented by k_{r1} and k_1 or k_{r2} and k_2.

In order to calculate k_L, the boundary condition should be applied. On the surface of the antenna, the electric field in the z direction is 0. On the surface of the sheath, the electric field in z direction is continuous, and the magnetic field in ϕ direction is continuous. The equations of boundary condition are

$$E_{z1}(r=a) = 0, \quad (13)$$
$$E_{z1}(r=b) = E_{z2}(r=b), \quad (14)$$
$$H_{\phi 1}(r=b) = H_{\phi 2}(r=b), \quad (15)$$
$$E_{z2}(r=c) = E_{z3}(r=c), \quad (16)$$
$$H_{\phi 2}(r=c) = H_{\phi 3}(r=c). \quad (17)$$

Substitute the electromagnetic field formulas into the boundary conditions, the equation which is contained k_{r1}, k_{r2} can be obtained. By applying the thin wire approximation and $|k_1|<<|k_3|$, the wave number k_L along the infinite length sheath is given by

$$k_L=k_1\sqrt{1+\frac{1}{ln(b/a)+n_{12}ln(c/b)}\frac{H_0^{(1)}(k_3c)}{k_3cH_1^{(1)}(k_3c)}} \quad (18)$$

where,

$$n_{12}=k_1^2/ k_1^2. \quad (19)$$

Since the sheathed region of the dipole antenna can be regarded as a transmission line, the model can be considered as a limited loaded transmission line.

C. *Results of input impedance*

In the case of full sheath dipole antenna, it can be considered that the model consists of two transmission lines of length L, which ends is open. The function of input impedance is given by

$$Z_{in}=j2Z_{ca}\tan k_L L. \quad (20)$$

The associated characteristic impedance of the transmission-line Z_{ca} is given by

$$Z_{ca}=\frac{\zeta_1 k_L}{2\pi k_1}\left[ln(b/a)+n_{12}^2 ln(c/b)\right] \quad (21)$$

where,

$$\zeta_1=\omega\mu_0/k_1. \quad (22)$$

The Figure 2 shows the results of the input impedance by theoretical analysis and the FDTD analysis in the case of the full sheath antenna. The theoretical results are represented by red line, and FDTD results are represented by blue line. The solid lines represent resistance, while the dashed lines represent reactance. The results of the theory almost agree with the results of the FDTD analysis in all frequency band.

In the case of half sheath dipole antenna, it can be considered that the model consists of two transmission lines of length l, which the ends is shorted by seawater because of its high conductivity. The function of input impedance is given by

$$Z_{in}=-j2Z_{ca}\cot k_L l. \quad (23)$$

The Figure 3 shows the results of the input impedance by theoretical analysis and the FDTD analysis in the cases of half sheath antenna. Although in the low frequency band, the results of theory have some differences with FDTD results, the results of the theory almost agree with the results of the FDTD analysis in high frequency band. This difference is caused by the exposed conducting wire of the antenna. In addition, it is shown that the input impedance will change greatly depending on the presence or absence of exposed structure.

II. Theoretical analysis of propagation loss in seawater

A. *Proposed method*

From view point of current distribution, sheath dipole antenna can be considered as infinitesimal dipole at frequency of kHz band. Therefore, the theoretical analysis of propagation loss in the case of infinitesimal antenna can be used for the half sheath dipole antennas. A new method is proposed by combing full-wave and theoretical analysis to estimate received power in longer distance. In the first step, full-wave analysis is used to calculate received power when the distance between the two antennas is short. In the second step, relative magnitude curve can be obtained by using theoretical analysis. Offset the strength of infinitesimal dipole field by the received power which is obtained in Step 1, received power in longer distance can be estimated.

B. *Verification of proposed method*

By using FDTD analysis, the result of maximum received power is shown in Figure 4. Two half sheath dipole antennas are placed 2 m below the sea, and distance between them is 2 m. The maximum received power is obtained under conjugate matching condition. When the incident power is 0 dBm, the received power is -48.3 dBm at 100 kHz. If the distance between two antennas becomes larger, the calculation time will increase greatly because the scale of model will become larger by using FDTD analysis.

By using theoretical analysis, electric field of infinitesimal dipole near sea's surface can be obtained. Tthree kinds of paths should be considered, which are direct path, reflect path and lateral path, as shown in Figure 5. The equations are shown as below [3]:

$$E_{d\varphi}^{he}=-\frac{Il}{4\pi\sigma}e^{-jkr}\left(-\frac{k^2}{r}+\frac{jk}{r^2}+\frac{1}{r^3}\right) \quad (24)$$

$$E_{r\varphi}^{he}=R_{TE}\frac{Il}{4\pi\sigma}e^{-jkr_r}\left(-\frac{k^2}{r_r}+\frac{jk}{r_r^2}+\frac{1}{r_r^3}\right) \quad (25)$$

$$E_{i\varphi}^{he}=\frac{Il}{\pi\sigma}e^{-jk(z_t+z_r)}\left(\frac{jk_0}{\rho^2}+\frac{1}{\rho^3}\right) \quad (26)$$

By using the received power in a short distance and the relative magnitude, received power in longer distances can be estimated.

The estimation of maximum received power is shown in Figure 6. Electric field strength is offset by -48.3 dBm, the maximum received power when distance between two antennas is 2 m at 100 kHz by FDTD analysis. Estimated received power is -123.4 dBm when the distance becomes 10 m. FDTD analysis is used to verify whether the result is correct. After 36 hours of calculation, -125.3 dBm is obtained.

The result obtained by proposed method is almost agree with FDTD result, and the calculation time is reduced greatly.

III. Conclusion

In this paper, input impedance and received power of full-sheath and half sheath dipole antenna is discussed and effective theoretical formulas based on transmission line theory have been derived. In addition, a new method is proposed to estimate received power by using full-wave and theoretical analysis. Received power was estimated by proposed method effectively. Calculation time for large scale models was greatly reduced.

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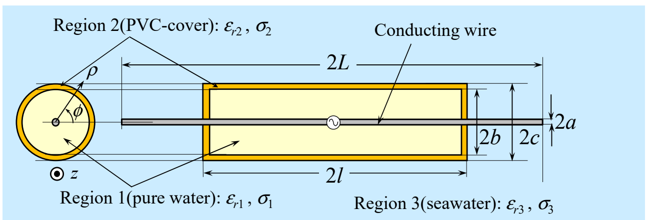

Fig. 1 Structure of sheathed dipole antenna with PVC-cover in seawater.

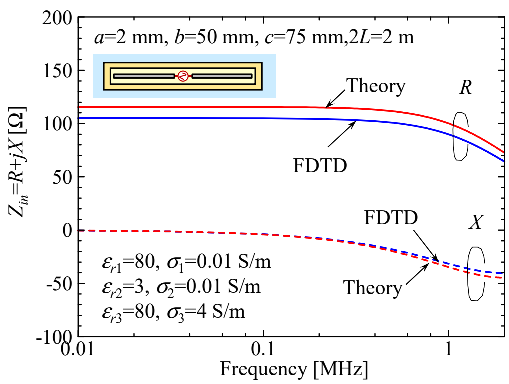

Fig. 2 Input impedance (full sheath)

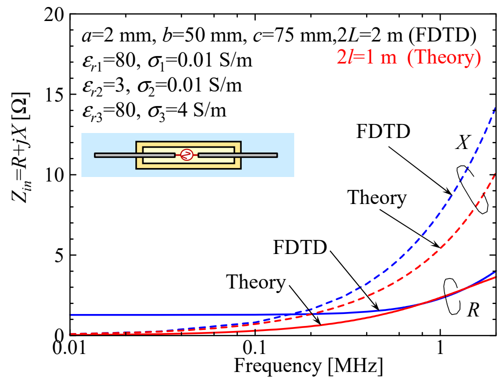

Fig. 3 Input impedance (half sheath)

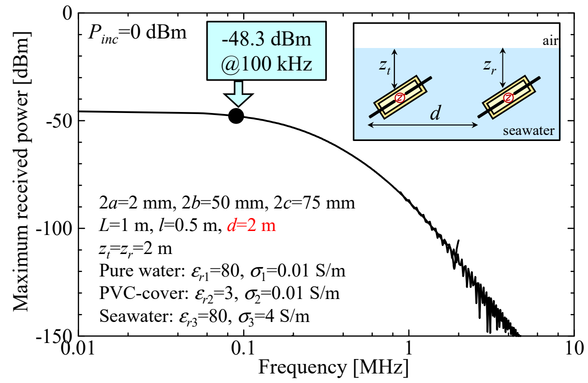

Fig. 4 Maximum received power obtained by FDTD when d=2 m

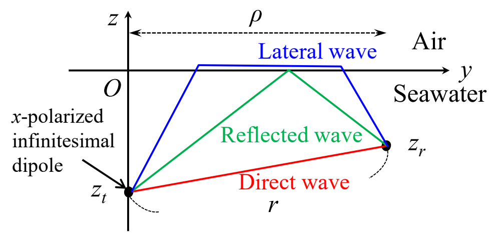

Fig. 5 propagation model of infinitesimal dipole

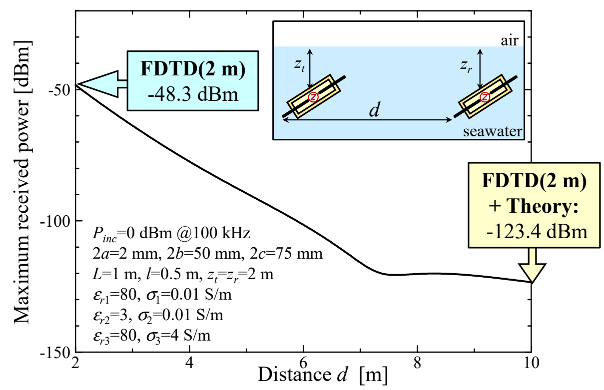

Fig. 6 Maximum received power obtained by proposed method