A VIRTUALLY CONICAL TRANSMISSION-LINE MODEL FOR OPEN-ENDED COAXIAL PROBES

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1. Introduction

An effective sensor to measure electrical properties of soil or rock in operation site may be open-ended coaxial probe. In our laboratory, the design and experiment of an open-ended coaxial probe were performed to measure complex permittivity of dry sand which was used as background medium in our GPR experiment. The reflection coefficients produced at the probe opening are measured by using an automatic network analyzer. And then the complex permittivity of the contacted material is calculated by inserting the reflection coefficients into an adequate one among several conversion models[1,2]. A rigorous modal analysis provides an integral equation to the aperture admittance at the probe opening as a function of the complex permittivity of a contacted material[3]. But the integral conversion is required of tremendous computation time and affected from weak stability due to measurement error. In this paper, a virtually conical TL(transmission-line) model is implemented by enhancing the advantages posed in the imaginary TL model[4]. Both of numerical simulations and actual experiments are performed to assure the validity of the suggested conversion model.

2. Virtually conical transmission-line model

Fig. 1 shows the cross section of an open-ended coaxial probe contacting with dry sand of relative permittivity e_m. The coaxial line of inner radius a, outer radius b, and relative permittivity of insulating material e_c is terminated by a flat conducting flange of radius R. The reflection coefficients can be calculated easily in a broad frequency band by applying the FDTD method in the discretized region, as shown in Fig. 1.

The measurement of the reflection coefficients Γ_m is performed by connecting an automatic network analyzer to the coaxial line at $z = -C$. Fig. 2 illustrates a virtually conical transmission line as a new equivalent probe model. Two unknown parameters Y_{eq} and D denote an equivalent admittance of the probe discontinuity at $z=0$ and the length of the conical TL, respectively, as

$$Y_{eq} = Y_c \frac{1-\Gamma_m e^{j2b_cC}}{1+\Gamma_m e^{j2b_cC}} - jY_m \tan(b_m D) \qquad (1)$$

$$D = \frac{1}{b_m} \tan^{-1}\left[\frac{Y_c(1-\Gamma_m e^{j2b_cC})/(1+\Gamma_m e^{j2b_cC}) - Y_{eq}}{jY_m}\right] \qquad (2)$$

In (1) and (2), there are three unknown parameters Y_{eq}, D, and e_m. For simplicity, air and pure water are selected as reference materials because those relative complex permittivities e_1 and e_2, respectively, are well known. Then those reflection coefficients Γ_1 and Γ_2 are measured by contacting to the probe one by one. Y_{eq} and D are calculated numerically by using such two relations as the known e_1 $\rightarrow$ the measured Γ_1 for air and the known e_2 $\rightarrow$ the measured Γ_2 for pure water.

After measuring Γ_m for dry sand, one may evaluate e_m by solving the following equations

$$e_m = C_{con} \frac{Y_c \dfrac{1-\Gamma_m e^{j2b_cC}}{1+\Gamma_m e^{j2b_cC}} - Y_{eq}}{jwD/c_0} x \cot(x) \qquad (3)$$

where C_{con} and c_o denote the characteristic impedance of the conical TL and the velocity of light in air, respectively.

$$x = \frac{wD}{c_0}\sqrt{e_m} \qquad (4)$$

3. Experimental results and discussions

An open-ended coaxial probe is manufactured according to the design data obtained from the FDTD simulation. Our probe calibration is very simple. First, we obtain the phase difference between the reflection coefficients of pure water measured by our probe and calculated by using the FDTD method. Next, the phase difference is subtracted from the phase of measured Γ_m of dry sand.

Applying the corrected Γ_m into (3), and then solving (3) numerically provide relative complex permittivity e_m of dry sand. The Korea Research Institute of Standards and Science provides us the reference data of e_m, which are measured by using a more accurate device than the open-ended coaxial probe. In Fig. 3, the bold lines denote the reference data of e_m of dry sand. The comparison results in Fig. 3 illustrate our conical TL model more accurate than the integral model. Furthermore, as shown in Table 1, the computation time for e_m conversion in our conical TL model reveals more faster than the integral model which has to be solved by applying the moment method iteratively.

Table 1. Comparison of two conversion models in view of measurement error and computation time.

	Measurement Error $\left(\frac{\left\|\left|e_m^*\right|-\left|e_{ref}\right|\right\|}{\left|e_m^*\right|}\right)$	Computation Time (sec/frequency)
Integral Model	1.1112×10^{-1}	900 1200
Conical Model	6.6004×10^{-3}	10 15

4. Conclusion

A virtually conical TL model is suggested as a new equivalent model of open-ended coaxial probe. A simple calibration scheme is also developed to suppress the error posed in the reflection coefficient measured by our open-ended coaxial probe. Actual measurement of the complex permittivity of dry sand assures the new equivalent model more accurate and faster than the integral model.

References

[1] M. A. Stuchly and S. S. Stuchly, "Coaxial line reflection methods for measuring dielectric properties of biological substances at radio and microwave frequencies- A review," *IEEE Trans. Instrum. Meas.*, vol. **I**M-29, no. 3, pp. 176-183, Sept. 1980.

[2] D. Berube, F. M. Ghannouchi, and P. Savard, "A comparative study of four open-ended coaxial probe models for permittivity measurements of lossy dielectric/biological materials at microwave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-44, no. 10, pp. 1928-1934, Oct. 1996.

[3] C. L. Pournaropoulos, *A Study on the Coaxial Aperture Electromagnetic Sensor and Its Application in Material Characterization*, Ph.D. Dissertation, Univ. Wisconsin-Milwaukee, 1996.

[4] F. M. Ghannouchi and R. G. Bossio, "Measurement of microwave permittivity using a six- port reflectormeter with an open-ended coaxial line," *IEEE Trans. Instrum. Meas.*, vol. IM-38, no. 2, pp. 505-508, Apr. 1989.

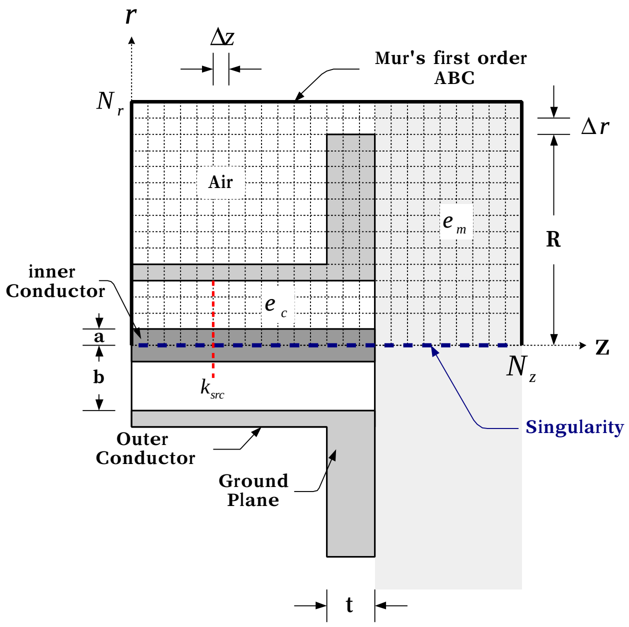


Fig. 1. Geometry of an open-ended coaxial probe contacted by dry sand.

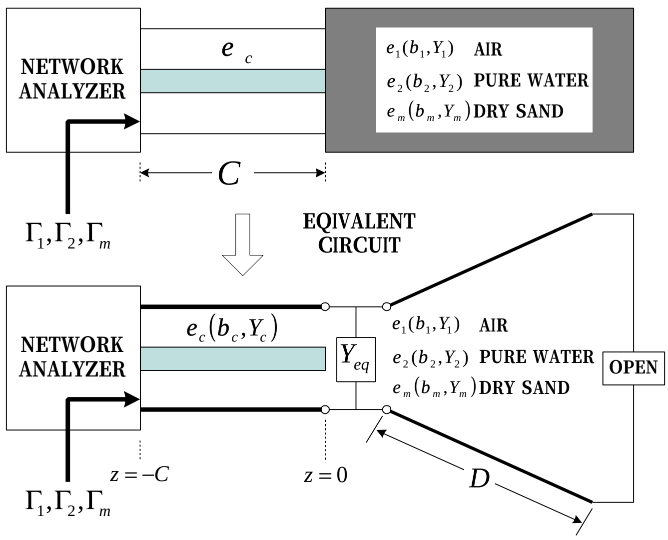
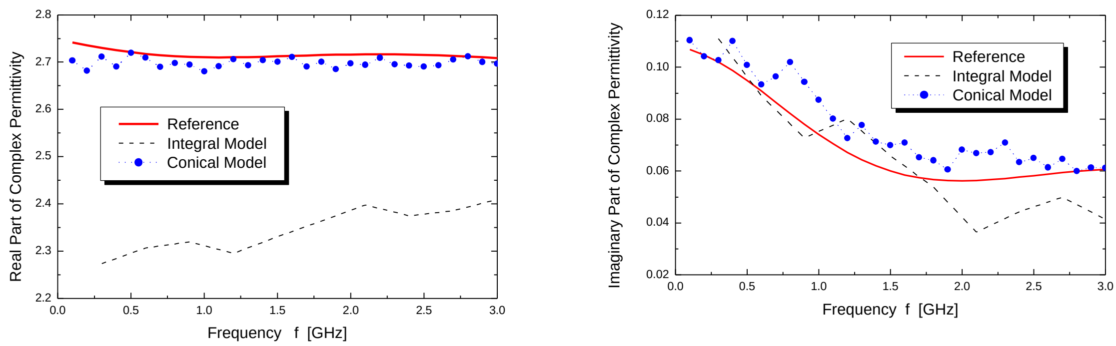


Fig. 2. An equivalent model consisting of virtually conical transmission line.



(a) real parts. (b) imaginary parts.

Fig. 3. Comparison of relative permittivities of dry sand converted by two different models.