20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Analysing the effect of conical coaxial probe angle in dielectric permittivity measurement

Homa Arab[1] and Cevdet Akyel[1]

[1]*Ecole Polytechnique of Montreal, QC, Canada, ,*
arab-salmanabadi.homa@polymtl.ca, cevdet.akyel@polymtl.ca

Abstract – **The aim of this paper is to study the effect of using different cone angles of a conical type coaxial probe in measuring dielectric properties of materials. Reflection coefficient, impedance and dielectric permittivity of six different angles of an open ended coaxial lines are studied. Using probes of sharper cone angles (sharper tips) allows for easier penetration into wide range of biological tissue types, which is an important feature in many biological applications. To demonstrate the accuracy of the numerical model, a parallel experimental study was carried out in the laboratory for the different cone angles. The results are compared and show excellent agreement. Moreover, the end results demonstrate that open-ended conical coaxial probes can be successfully used especially at low frequencies with the advantage of increased accuracy and sensitivity for sharper angles.**

I. INTRODUCTION

In several biomedical and industrial applications, it is necessary to know the dielectric properties of biological tissue types and semi-rigid materials like rubber, some plastics, and organic materials (ex: dairy, butter, ect. for measuring moisture content). A certain number of method exist in the literature [1–4]. However, a new type of conical coaxial probe that is filled with dielectric PTFE (Teflon) is studied in this research. The conical coaxial probe is a precise non-destructive determination at microwave and radio frequencies and it is less effected by unavoidable temperature variation when compared to standard flat-plan open-circuit coaxial-probe. This paper present a finite element method (FEM) to evaluate capacitance and resistance of an conical coaxial probe in contact with a homogeneous medium. The FEM Method is well adapted to deal with this class of problems, due to its flexibility for handling complex geometries. The equations are discretized using nodal and edge elements and Galerkin method is chosen for finding numerical solutions to Helmholtz equations where the solution residue is minimized giving rise to the well-known weak formulation of problems. The Conical probe is modelled by three capacitance for coaxial probe body, conical aperture, fringing capacitance for material under test(MUT), and a resistance related to radiation in MUT [5, 6]. The effect of multiple reflection, attenuation in the wave, and mismatches between the connector plug and the coaxial cable were considered using regression analysis. The calculated static as well as frequency dependent capacitances and resistance are compared with the available theoretical and experimental results for different angles [7].

II. STRUCTURE DEFINITION

The 2-dimensional electromagnetic structure of conical-type open-ended coaxial probe and equivalent circuit shown in Figure 1 is considered. The global constants related to structure and material properties are presented in Table 1. The probes are made by POLY-GRAMES technicians Department of Electrical Engineering of Ecole Polytechnique of Montreal. The calibration elements were the air (open standard), the short standard, and matched load (Agilent 85033E kit).
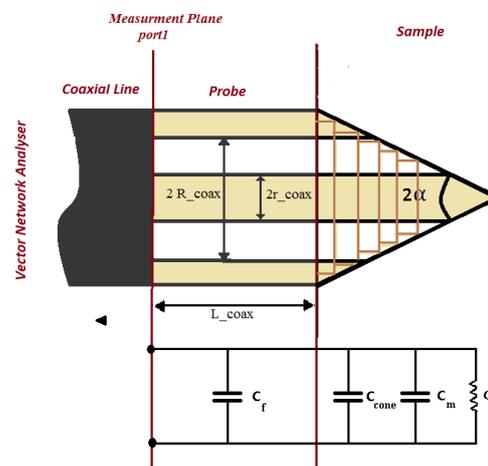

Fig. 1. Conical coaxial probe geometry-equivalent circuit

Table 1. Handmade Probes and network analyzer.

Name	Expression	Description
r_{coax}	0.455 [mm]	Coax inner radius
R_{coax}	1.49 [mm]	Coax outer radius
L_{coax}	250 [mm]	Length of conical coax probe
f	300 [MHz]- 3 [GHz]	Frequency
$2 \times \alpha$	60°	Cone Angle

Fig. 2. Handmade Probes and network analyzer.

Some of the experimental setup that was used during the research is shown in Figure 2.

III.   ANTENNA MODEL

In the antenna model, the cone part of the conical probe is modelled by C_{cone}, while the material under test (MUT) is modelled by a capacitor $C_m = C_f + \varepsilon C_0$ and a conductor G connected in parallel to the capacitor for modelling the radiation in MUT [3, 8]. The normalized admittance of the equivalent circuit at the aperture port figure 1 is given by:

$$\frac{Y}{Y_0} = j\omega C_{cone} Z_0 + j\omega C_m Z_0(\omega, \varepsilon_0) + Z_0 G(\omega, \varepsilon_0).$$

(1)

For a coaxial probe immersed in a lossy medium it has been shown in [9–11] that:

$$Y(\omega, \varepsilon) = \sqrt{\varepsilon} Y(\sqrt{\varepsilon}\omega, \varepsilon_0).$$

(2)

Therefore, equation 1 may be written:

$$\frac{Y}{Y_0} = j\omega C_{cone} Z_0 + j\omega C_f Z_0 + j\omega\varepsilon C_0 Z_0 + Z_0 G \varepsilon^{5/2}.$$

(3)

The analytical computation of C_{cone} part is complicated due to the different geometrical parameters of the structure. For this reason, we will use an approximate alternative method to do the calculation of C_{cone}. The first technique being used here is comparing the reflection coefficient at port $B - B'$ of two different probe types, flat and conical coaxial probes. The difference between the admittance of both of the probes is related to the conical part of the conical coaxial probe capacitance. The second method is dividing the aperture into many thin layers and each layer can be approximated by a constant radius which is an elegant way to calculate C_{cone} accurately. The results of both methods are in good agreement as shown in Figure 3.
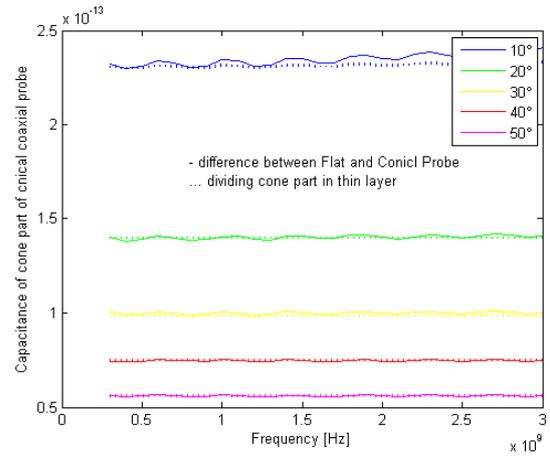

Fig. 3.   Capacitance of cone part for different angle of conical coaxial probe.

In Figure 4 C_0 and C_f are illustrated separately. Numerical methods are used to calculate values of the total fringing capacitance C_m for both Air and Water. From this data, the values of C_0 and C_f are obtained by solving the simultaneous linear equation $C_m = C_f + \varepsilon C_0$.
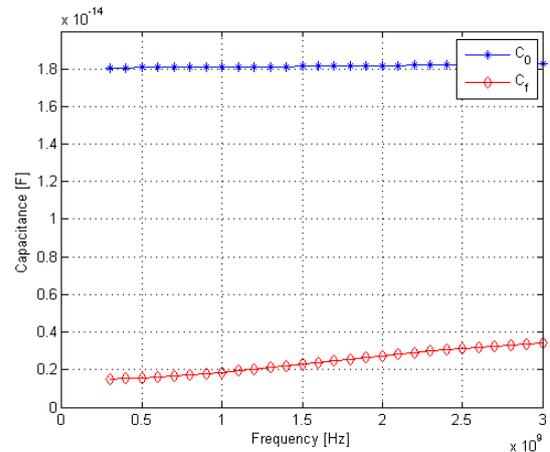

Fig. 4. Capacitances of the fringing field - Conical coaxial probe ($\alpha = 30^\circ$) [F].

As we can see for coaxial line whose dimensions are

small compared to a wavelength, C_f and C_{cone} are frequency independent, while C_0 and G are dependent on frequency.
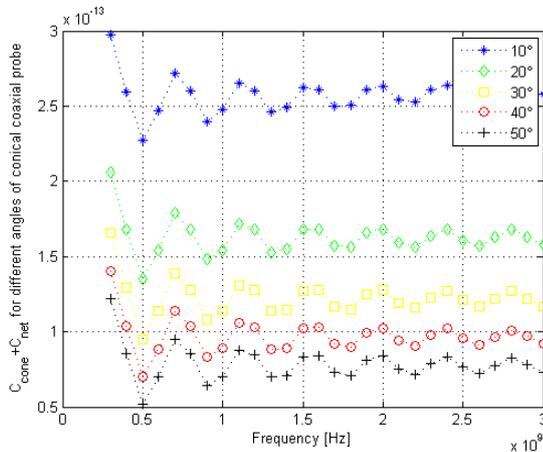

Fig. 5. $C_{cone} + C_{net}$ *for different angles of conical coaxial probe [F].*

Figure 5 show the sum of measured capacitance for cone part of coaxial probe body and fringing capacitances for various cone angles, α, of coaxial sensor.

IV. RESULTS AND DISCUSSION

Figures 6 and 7 show relative permittivity and conductivity for three different materials (Ethanol, Methanol, and Butanol) obtained with a conical type open-ended coaxial probe. These permittivities are calculated from the reflection coefficient measured in aperture port of conical coaxial probe. The use of such model is a good approximation for large range of permittivities at radio and microwave frequencies.
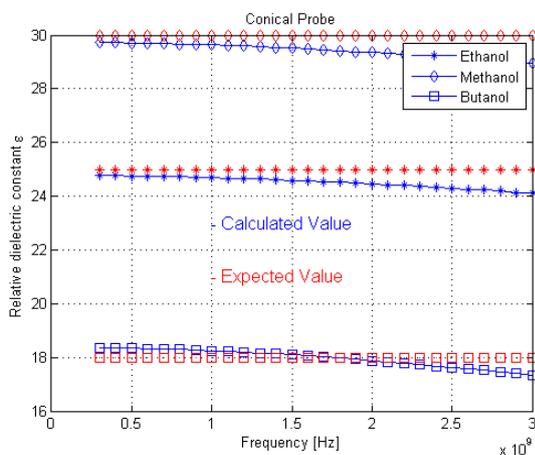

Fig. 6. *Relative dielectric constant for open ended conical coaxial probe (cone angle 30 degree) versus frequency.*
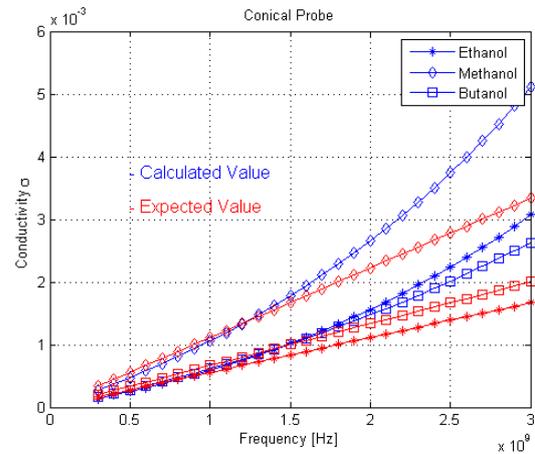

Fig. 7. *Conductivity for open ended conical coaxial probe ($\alpha =$ 30°) versus frequency [S/m].*

Using probes of sharper cone angles (sharper tips) allows for easier penetration into wide range of biological tissue, which is an important feature in many biological applications. The results in figures 5 and 3 demonstrate that for sharper cone the capacitance increase and it is the main reason for the increase of accuracy and sensitivity. Small changes in properties of materials show more effect in sharper conical coaxial probe. Thus, open-ended conical coaxial probes can be successfully used especially at low frequencies with the advantage of increased accuracy and sensitivity for sharper angles. These results also allow the quantification the upper and lower frequency limit for different angles in which the conical type coaxial probe can be applied. Moreover, by analyzing the electric and magnetic fields distribution at the probe aperture material interface and determine the complex reflection coefficient, or scattering function S_{11}, at the connector of the conical type open-ended coaxial line, the optimal configuration for probe can be determined.

V. CONCLUSION

In this work, the effects of the cone angle of conical coaxial probe have been intensively studied and reported. The advantages of the sharper probe are not only in its easy insertion in material and biological application, but also the accuracy and sensitivity of this probe improved in the low frequency range in compare to flat plan open circuit coaxial probe.

VI. REFERENCES

[1] J. Sheen, *Microwave dielectric properties measurements using the waveguide reflection dielectric resonator," in Instrumentation and Measurement Technology Conference Proceedings*, 2007. IMTC 2007. IEEE. IEEE, 2007, pp. 1-4.

[2] P. I. Dankov, *Two-resonator method for measurement of dielectric anisotropy in multi- layer samples*, Microwave Theory and Techniques, IEEE Transactions on, vol. 54, no. 4, pp. 1534-1544, 2006.

[3] F. Lan, C. Akyel, et al. (1999). *A six-port based on-line measurement system using special probe with conical open end to determine relative complex permittivity at radio and microwave frequencies. Instrumentation and Measurement Technology Conference*, 1999. IMTC/99. Proceedings of the 16th IEEE, IEEE.

[4] Wagner, N., Schwing, M, Scheuermann, A. *Numerical 3-D FEM and Experimental Analysis of the Open-Ended Coaxial Line Technique for Microwave Dielectric Spectroscopy on Soil*, Vol. 52, No. 2, 1064–1076, 2014.

[5] T. Marsland and S. Evans, *Dielectric measurements with an open-ended coaxial probe*, in IEE Proceedings H (Microwaves, Antennas and Propagation), vol. 134, no. 4. IET, 1987, pp. 341-349.

[6] G. Panariello, L. Verolino, and G. Vitolo, *Efficient and accurate full-wave analysis of the open-ended coaxial cable*, Microwave Theory and Techniques, IEEE Transactions on, vol. 49, no. 7, pp. 1304-1309, 2001.

[7] You. KY, Salleh. J and Abbas. Z, *Effects of Length and Diameter of Open-Ended Coaxial Sensor on its Reflection Coefficient.*, RadioEngineering 21(1), 2012.

[8] D. Berube, F. 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*, Microwave Theory and Techniques, IEEE Transactions on, vol. 44, no. 10, pp. 1928-1934, 1996.

[9] G. Deschamps, *Impedance of an antenna in a conducting medium*, Antennas and Propagation, IRE Transactions on, vol. 10, no. 5, pp. 648-650, 1962.

[10] M. Brandy, S. Symons, and S. Stuchly, *Dielectric behavior of selected animal tissues in vitro at frequencies from 2 to 4 ghz*, Biomedical Engineering, IEEE Transactions on, no. 3, pp. 305-307, 1981.

[11] R. Keam and J. Holdem, *Permittivity measurements using a coaxial-line conical-tip probe*, Electronics Letters, vol. 33, no. 5, pp. 353-355, 1997.