SoftwareX 9 (2019) 187–192

Contents lists available at ScienceDirect

SoftwareX

journal homepage: www.elsevier.com/locate/softx

Original software publication

NDECOAX: A software package for nondestructive evaluation of stratified dielectric media

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ARTICLE INFO

Article history:
Received 12 October 2018
Received in revised form 1 February 2019
Accepted 1 February 2019

Keywords:
Coaxial probe
Nondestructive evaluation (NDE)

ABSTRACT

This article presents a software package based on the C++ language for accurate computation of material properties of a stratified media using an open ended coaxial probe (OECP). Since OECP is one of the most commonly used sensors for evaluation of materials today, the program developed can be customized for real time nondestructive evaluation of materials. The main contribution of this article is a computationally efficient software for solving an infinite domain integral with multiple singularities based on plane wave spectrum theory. The computed results for aperture admittance of the coaxial probe using the developed software show good agreement with both measurements and results from a commercial solver using the finite element method (FEM). It is also proved that, the execution time per frequency point of the developed code is much faster than FEM.

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Code metadata

Current code version	https://github.com/ElsevierSoftwareX/SOFTX_2018_197
Permanent link to code/repository used for this code version	Attached NDECOAX.zip file
Legal Code License	GNU General Public License (GPL)
Code versioning system used	None
Software code languages, tools, and services used	C++ under Linux platform
Compilation requirements, operating environments & dependencies	gcc or g++ for C++ compiler and gnuplot for generation of plots
If available Link to developer documentation/manual	Provided readme file in NDECOAX.zip
Support email for questions	p_mathur@blr.amrita.edu

1. Motivation and significance

Nondestructive evaluation enables the study of the internal structure, geometry, and bulk material properties of stratified media. The use of electromagnetic waves, especially, microwave frequencies enables one to penetrate deeply into materials [1]. The evaluation is based on a sensor which interacts with the external dielectric media. The most commonly used sensors for noninvasive evaluation of materials are open ended coaxial probes (OECP), open ended rectangular waveguides (OERW) and open ended circular waveguides (OECW) [2–7]. Of the above sensors, open ended coaxial probes (OECP) are the simplest and most cost effective and have been widely used as proximity probes for microwave based nondestructive evaluation (NDE) applications [8]. In the past, researchers have used analytical analysis, semi-analytical full-wave methods and numerical simulation for in-depth studies of stratified layers [4–8]. However, for practical evaluation and characterization of a stratified media, a more robust broadband electromagnetic model describing the near field interaction between the sensor and the composite structure is required.

This article presents a C++ implementation of a fast and accurate method to calculate the near field aperture admittance for nondestructive evaluation of stratified media. The formulation of the problem is based on plane wave spectrum theory [9], which

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https://doi.org/10.1016/j.softx.2019.02.001
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in its original form yields an integral for aperture admittance computation of the multilayer dielectric media [10]. This integral is challenging due to multiple singularities of the integrand and convergence issues due to the integration domain extending to infinity, especially when the media is lossless or only slightly lossy. The software package, named NDECOAX, would be the first of its kind to be publicly available for the analysis of generic multi-layered dielectric media in the vicinity of OECP. The accuracy of the developed code has been compared to and agrees well with experimental results available. The accuracy of simulated results using the developed software for many different geometries is also comparable to a commercial finite element method based solver. However the execution time of the developed software is over 200 times faster than the commercial solver. The proposed software is therefore useful for fast and accurate characterization of materials from measurement of the aperture admittance. In addition, the proposed software can be used to monitor the electrical properties of a stratified media in real time due to its excellent computational efficiency. This article is organized as follows: Section 2 provides the theoretical background of the problem statement and proposed solution, the program description is given in Section 3. Section 4 describes numerical results obtained for low loss and high loss stratified media, Section 5 discusses the impact of the proposed software, and is followed by conclusions in Section 6.

2. Theoretical background

The multilayered structure shown in Fig. 1, describes the problem set-up. A coaxial line penetrates a circular ground plane, placed adjacent to the layered structure such that the coaxial probe aperture, lies in the *xy*-plane at $z = z_0$ with the inner conductor radius a and outer conductor radius b and filled a lossless dielectric of permittivity ϵ_c. The layers $i = 1, 2 \dots N$ are indexed according to their spatial ordering along the z axis with each layer defined by its complex relative permittivity ϵ_i, relative permeability μ_i and layer thickness d_i. The last layer $z > z_N$ is free space extending to infinity. We assume that each layered media is non-magnetic such that $\mu_i = \mu_0$ and the dominant transverse electromagnetic (*TEM*) mode is present inside the probe [10]. The reflection coefficient S_{11} at the open ended aperture for *TEM* mode incidence can be written as,

$$S_{11} = \frac{Y_{\mathrm{coax}} - Y_A}{Y_{\mathrm{coax}} + Y_A} \tag{1}$$

where, Y_A is the aperture admittance and Y_{coax} is the characteristic admittance of coaxial probe given as,

$$Y_{\mathrm{coax}} = \frac{2\pi}{\ln(\frac{b}{a})}\sqrt{\frac{\epsilon_0\epsilon_c}{\mu_0}} \tag{2}$$

where, ϵ_c is the dielectric constant of the lossless material filling the coaxial probe, see Fig. 1. According to the plane wave spectrum theory, the aperture admittance Y_A depends on the polarization of the incident plane wave on the external stratified dielectric media. In [10], it is shown that, with the dominant *TEM* incident on the aperture, the structure only excites *TM* polarized waves on the external multilayer structure. The terminating aperture admittance in presence of multilayered dielectric layers is obtained by applying the complex Poynting's theorem and continuity of power flow at the aperture cross section, yielding,

$$Y_A = M\int_0^\infty f_{TM}(\beta)Y_{in}(\beta, z_0)\frac{d\beta}{\beta} \tag{3}$$

where, $M = \frac{2\pi}{[\ln(b/a)]^2}$, $f_{TM}(\beta) = [J_0(kb\beta) - J_0(ka\beta)]^2$, J_0 is the Bessel function of the first kind, k is the wave number inside the OECP probe and β is the integration variable, which depends on the angle of incidence. $Y_{in}(\beta, z_0)$ in (3) is the surface input admittance at $z = 0$ plane, determined by the external media and obtained recursively as

$$Y_{in}(\beta, z_{i-1}) = Y_{\beta_i}\left[\frac{Y_{in}(\beta, z_i) + jY_{\beta_i}\tan(k_{z_i}d_i)}{Y_{\beta_i} + jY_{in}(\beta, z_i)\tan(k_{z_i}d_i)}\right] \tag{4}$$

where, $i = N, N-1, \dots, 2, 1$, with the initial condition $Y_{in}(\beta, z_N) = Y_0\frac{1}{\sqrt{1-\epsilon_c\beta^2}}$ for free space backing. Y_{β_i} in (4) is the ith layer admittance and depends not only on the layer material property but also on β and given as:

$$Y_{\beta_i} = Y_0\frac{N_i^2}{\sqrt{N_i^2 - \epsilon_c\beta^2}} \tag{5}$$

where, Y_0 is the free space admittance, $k_{z_i} = k_0\sqrt{N_i^2 - \epsilon_c\beta^2}$, represents the axial wave number of the external dielectric layer, k_0 is the free space propagation constant and N_i is the complex index of refraction of each layer outside the coaxial probe.

Problem statement and proposed solution

To compute the aperture admittance, we have to evaluate the contour integral along the real axis in the complex β plane described in (3). However, the integration path passes through or near multiple singularities if the layer media parameters are lossless or low loss, respectively, in the region $0 \leq \mathrm{Re}[\beta] \leq \sqrt{\epsilon_{\max}}$, where $\epsilon_{\max}$ is the maximum relative dielectric constant of the stratified media [10]. The condition $|\beta| > 1$, which corresponds to evanescent plane waves, also needs to be incorporated in (3) for accurate admittance at the aperture. This makes the solution of the integral even more challenging due to slow convergence of integrand as $\beta \to \infty$. However, these issues which are more prominent in lossless and low loss cases, were not dealt with in [10]. The proposed software package follows previous work [11,12], where a two step integration method is applied for computing the infinite domain integrals over the real axis with multiple singularities and slowly convergent integrands as $\beta \to \infty$. In [11], a method is proposed for finding the interaction of an open ended circular waveguide with a layered media based on the method presented in [12]. This paper, however, deals with the evaluation of aperture admittance for an open ended coaxial probe (OECP), since the OECP is one of the most commonly used sensors for the noninvasive evaluation of materials. The expression for aperture admittance in the near field of the OECP (3) can be divided into two paths as [12],

$$\begin{aligned} Y_A = {} & M\overbrace{\int_0^\pi f_{TM}(\beta_\theta)Y_{in}(\beta_\theta, z_0)\beta_\theta{}'d\theta}^{I_0^g} \\ & + M\overbrace{\int_{\sec^{-1}g}^{\pi/2} f_{TM}(\beta_\alpha)Y_{in}(\beta_\alpha, z_0)\beta_\alpha' d\alpha}^{I_g^\infty} \end{aligned} \tag{6}$$

where, $\beta_\theta = 0.5\,g(1-\cos(\theta)) + jh\sin(\theta)$, $g = 1.1\sqrt{\mathrm{Re}(\epsilon_{\max})}$, $h = 10^{-11}k_0$ and $\epsilon_{\max}$ is the maximum relative dielectric constant of the external stratified layer. By splitting the integral in (3) according to (6), overcomes the singularity and infinite upper limit issue in (3). The first integral I_0^g, which may encounter multiple singularities along the integration path is efficiently evaluated using a deformed elliptical integration path. The elliptical path will ensure that all singularities are avoided, such that accurate results can be obtained. The second integration path, I_g^∞, although without singularities, but equally challenging, is evaluated by changing the integration variable to $\beta_\alpha = \sec(\alpha)$, yielding a finite upper limit for the integrand. Thus the proposed software efficiently solves

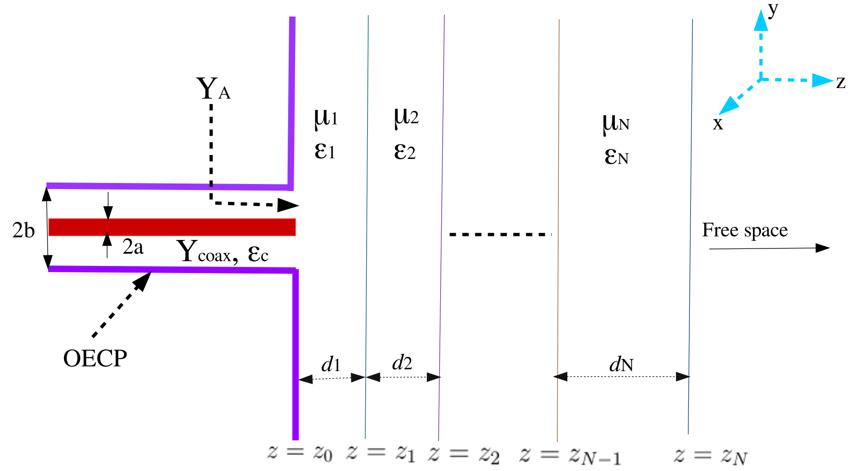


Fig. 1. An Open ended coaxial probe (OECP) with circular ground plane, radiating into N layers of stratified dielectric media.

the integral (3) via two integrals described in (6). Since both the integrals are transformed into definite integrals, they are evaluated numerically using the adaptive Gauss–Lobatto quadrature method described in [13], which will also take care of the oscillatory behavior of Bessel functions in both the integrands. The primary advantage of the proposed software is the fast computation of aperture admittance compared to other general purpose numerical approaches such as the finite element method (FEM). Therefore, the proposed software package will enable us to estimate permittivity of materials as an inverse problem faster than other numerical methods for nondestructive evaluation of materials.

3. Software description

Fig. 2, shows the structure of the C++ program for computing the aperture admittance of low loss and lossy multilayer media for nondestructive evaluation of materials. The implementation of the program is based upon the client–server model. The compilation of the program is done using *makefile* which in turn will generate an executable file *NDECOAX.exe*. The explanation of all the files contained in program are described in the following sections.

3.1. *LayeredMedia.cc*

This file contain the class functions of the C++ class *LayeredMedia* for setting different parameters such as dimensions and material properties of OECP and layered media. The integrands in (6) are also defined in this file through class functions. Therefore, this file must include the *Bessel.h* header file which contains the declaration of Bessel functions [14] required for calculation of integrands in (6).

3.2. *Calculate_admittance.cc*

This file contains the computation of each integral in (6). Various parameters set in the C++ class *LayeredMedia* and integrands are accessed through a class pointer *LayeredMedia** defined in this file. This file calls the numerical integration routines based on adaptive Gauss–Lobatto quadrature defined in *Integration.cc*. Therefore, this file includes the header file *Integration.h* where the functions for adaptive Gauss–Lobatto quadrature numerical integration are declared.

3.3. *NDECOAX.cc*

This file contain the *main()* function, in which the dimensions and material properties of the OECP and layered media are defined. For lossy dielectric media the dispersion characteristics of the material is read from a separate data file. All the parameters are passed to C++ class *LayeredMedia* through a class object defined in *main()* for each frequency. In addition, *main()* defines the parameters of integration such as path and tolerance of numerical integration and calls the integration functions defined in *Calculate_admittance.cc* by passing the *LayeredMedia* class object and integration parameters. The computed results of aperture admittance for each frequency are saved in the output file. Through run time unix system calls to plot utility *Gnuplot* [15], using an interface *Gnuplot_interface.cc*, developed and provided by the authors, various plots are generated.

3.4. *Utility functions*

Various utility functions required for the execution of the program are defined in the following files.

3.4.1. *Bessel.cc*

This file implements the accurate trigonometric expansions of Bessel functions of first kind and integer order for complex arguments.

3.4.2. *Integration.cc*

The program performs the integration of the function (6) using adaptive Gauss–Lobatto quadrature using the *quadl* function .

3.4.3. *Gnuplot_interface.cc*

Execution of the program will generate the data as well as plots using the plot utility *Gnuplot* through linux system calls.

4. Numerical results

In this section, we validate the output of NDECOAX with both experiments and commercially available Finite Element Method (FEM) based solver. We illustrate the accuracy and execution speed of our developed program for various material parameters and dimensions of lossy and low loss stratified media.

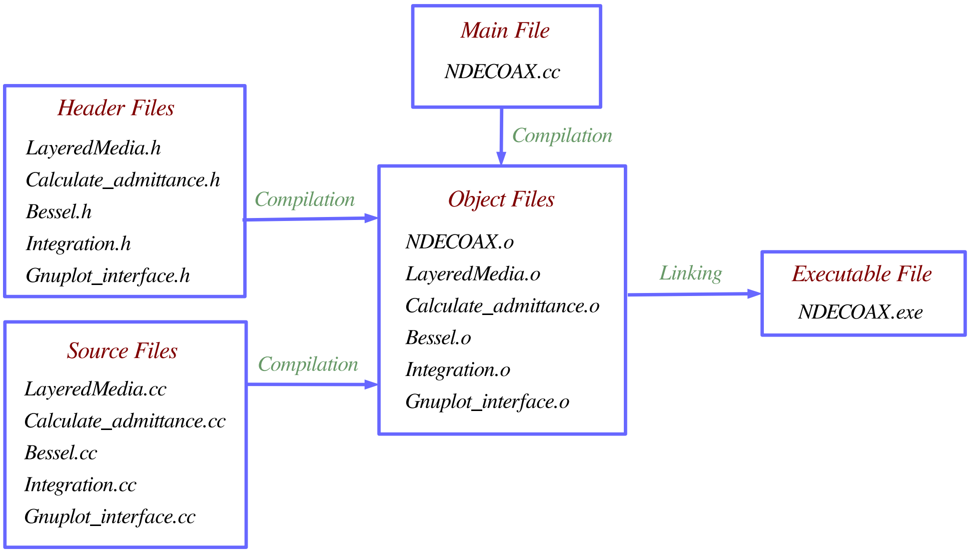
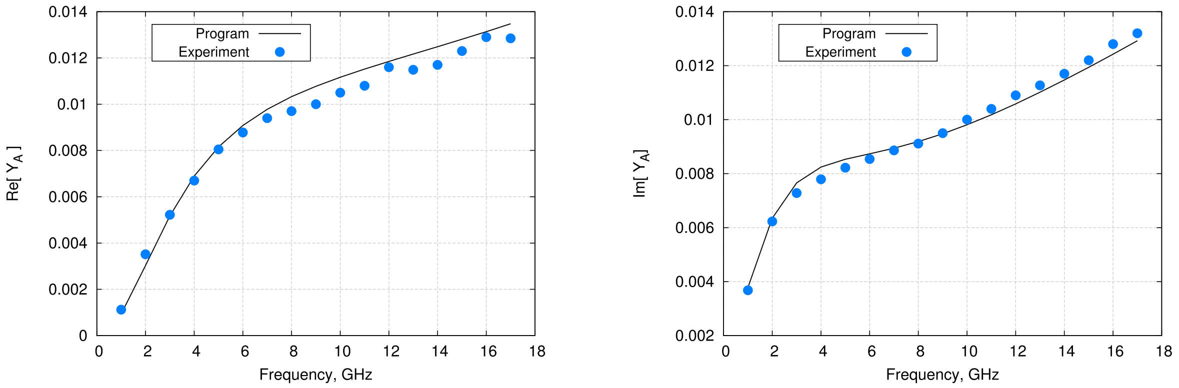


Fig. 2. Structure of the Program.



(a) (b)

Fig. 3. Validation of developed program for aperture admittances of open ended coaxial probe immersed in methanol with experiment [16], (a) Real part (b) Imaginary part.

4.1. Lossy media

The first test case we consider for validating our program is methanol of thickness 70 mm backed with free space. Therefore, the material under test can be considered as a single layer lossy dielectric media. The dielectric properties of methanol [16] are summarized by the empirical equation,

$$\epsilon = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \tag{7}$$

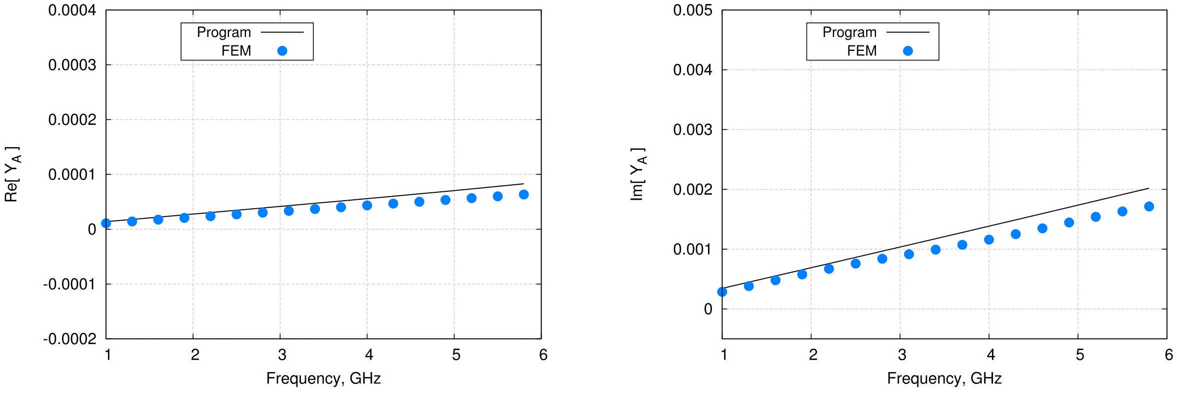
where, $\epsilon_\infty = 5.6$, $\epsilon_s = 32.6$, relaxation time $\tau = 4.8e^{-12}$ s, $\alpha = 0$ and ω is the angular frequency. The parameters of open ended coaxial probe used for the measurement is as follows : $a =$ 0.4 mm, $b = 1.14$ mm, $\epsilon_c = 1.58$, and ground plane diameter of 3 mm (approximately $0.1\lambda_0$) as mentioned in [16]. Fig. 3 shows the real and imaginary part of input admittance of OECP immersed in methanol. It is clear that the proposed method agrees well with measurements [16] for the entire frequency range considered.

4.2. Lowloss case

In the second test case for validating our program, we consider a low loss three layer dielectric media whose dielectric properties and thickness are given in Table 1. The parameters of open ended coaxial probe (OECP) used for the simulation is as follows : $a =$ 0.13 mm, $b = 0.95$ mm and $\epsilon_c = 5.5$. The result of the proposed method is compared with commercial HFSS software, which is based on the Finite Element Method (FEM) [17]. For the HFSS simulation, we used an Intel-I7 computer with 8 GB RAM with length of OECP of 15 mm, and ground plane and external layers diameter of 9 cm which is backed with free space (HFSS data file is attached as input file for validation). The reason for choosing the larger ground plane (approximately λ_0) is to incorporate the assumption of an infinite ground plane in the simulation [18]. The execution time of the HFSS solver, for a given accuracy constraint, depends on the mesh setting and drastically increases as the thickness of the external dielectric increases. The maximum number of adaptive passes is set as 10 with the maximum delta error of 0.01. The tolerance for numerical integration in our program was set at $1e^{-9}$. To solve this problem, HFSS took 33.5 s per frequency point where as our program generated the result in 0.17 s Therefore, the runtime of our program has an improvement factor of approximately 200

Table 1
Dielectric properties of low loss stratified media.

Layer no	Material	ϵ_r	tanδ	Thickness (mm)
1	Rubber	7.3	0.004	3.175
2	Teflon	2	0.0003	4
3	Acrylic	2.6	0.00043	11



(a) (b)

Fig. 4. Aperture admittances of open ended coaxial probe radiating in three layer lossless media, (a) Real part (b) Imaginary part.

compared to HFSS. Fig. 4 shows the real and imaginary part of input admittance at the OECP aperture adjacent to stratified layers. From Fig. 4, it is clear that the proposed method is capable of producing the same results as the FEM based solver within a percentage error of less than ±5%. The code provides the flexibility to the user for choosing any dimension and material filling of the open ended coaxial probe (OECP) for better electromagnetic interaction with the stratified media under test.

5. Impact

Nondestructive testing and evaluation is an emerging technique for evaluating various properties of a material and finds application in various engineering disciplines such as mechanical, civil, electrical, and aeronautical engineering. Since electromagnetic waves have better penetration at microwave frequency ranges, microwave reflectivity based material evaluation is an actively researched area, with considerable potential for commercialization [19]. Compared to other nondestructive techniques such as ultrasound, microwave reflectivity based material evaluation offers various advantages such as, high resolution, low cost, easy operation and rugged design. Among many microwave sensors, the open ended coaxial probe (OECP) is the simplest and most widely used sensor for material characterization. Since commercial OECP source codes for non-invasive evaluation are proprietary [20], the proposed method and the corresponding source code will offer a cost effective alternative for end users in the area of microwave based nondestructive testing and evaluation. The proposed software for modeling OECP and the source code under open source framework has been comprehensively validated with experimental data as well as with a commercially available electromagnetic simulator. The proposed software can also be easily extended for material characterization using open ended circular waveguides, which is gaining popularity among the researchers, due to its excellent coupling and penetration, without losing structural robustness [21].

6. Conclusions

NDECOAX is an efficient C++ program for accurate computation of material properties of a stratified media using an open ended coaxial probe (OECP) is presented in this article. NDECOAX will find application in nondestructive evaluation of materials based on OECP since OECP is one of the most commonly used sensors for evaluation of materials. The results shows good agreement with both measured results as well as with a commercial solver based on the finite element method (FEM). Since the execution time per frequency point of the developed code is approximately 200 times faster than FEM, the developed program can be customized for use in the real time nondestructive evaluation of materials.

Acknowledgments

This work is jointly supported by DST, Govt. of India under Visvesvaraya Ph.D. Scholar scheme (DIC/MeitY) and Indo-Swedish bilateral research scheme, Vinnova, Sweden (2015–04159).

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