Analysis of Transient Interaction of Electromagnetic Pulse with an Air Layer in a Dielectric Medium Using Wavelet-Based Implicit TDIE Formulation

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Abstract—The interaction of transient electromagnetic pulse with an air layer in a dielectric medium is formulated in terms of a time-domain integral equation and solved numerically via the method of moments. Previous related works pointed to the inherent inadequacy of the marching-on-in-time method in this case, but suggested no remedy. This paper explains why an implicit modeling scheme would work effectively in this case. It is also noted that the use of an implicit scheme would normally involve a solution of a very large and dense matrix equation. To alleviate this drawback of the implicit scheme, the use of a wavelet-based impedance-matrix-compression technique, which has facilitated in the very recent past solutions of time-domain problems with greater efficiency, is described.

Index Terms—Air layer, implicit formulation, time-domain integral equation, transient analysis, wavelet.

I. INTRODUCTION

Analysis of transient interaction of an electromagnetic pulse with a layer, characterized by a dielectric constant lower than that of the surrounding medium, is often required, e.g., in the study of human tissues and the investigation of underground air tunnels and inner faults in structures [1], [2]. This interaction problem can be formulated in terms of a time-domain volume integral equation, using the Green’s function of homogeneous unbounded space characterized by the lower phase velocity of the denser surrounding medium. In turn, the equation is solved numerically via the method of moments (MoM). However, application of an explicit modeling scheme and solving the resultant lower triangular matrix by a standard marching-on-in-time (MOT) method cannot, in this case, lead to the correct solution [3], [4]. This, as was noted in [5], is due to the fact that, in the explicit scheme, any spatial interval is larger than the distance traveled by the waves during the specified time interval. Consequently, propagation of high-phase-velocity waves cannot be provided for.

In this paper, we present a solution based on the implicit modeling scheme [6]–[9], which overcomes the deficiency of the MOT procedure, as well as the complexity involved in solving the implicit MoM equation. The solution is obtained via a novel method, which employs a spatio–temporal wavelet basis to facilitate an accurate solution simultaneously at all time steps within the time frame of interest. The wavelet-based MoM solution of the time-domain integral equation (TDIE) is effected via the iterative impedance-matrix-compression (IMC) procedure, which gradually constructs and solves a compressed version of the matrix equation until the desired level of accuracy is obtained [10]–[12].

This paper is organized as follows. Section II presents the problem and outlines the method of solution. Numerical results are given in Section III. Finally, a summary and conclusions are given in Section IV.

II. PROBLEM FORMULATION

The problem under consideration is the one-dimensional transient interaction of a Gaussian pulse of an electromagnetic plane wave with an air layer in a dielectric medium, as depicted in Fig. 1.

The medium has a dielectric constant $\varepsilon > \varepsilon_0$ and the air layer fills the entire space between planes $z = 0$ and $z = d$. The incident Gaussian pulse, propagating along the z-direction with its electric-field vector parallel to the surface of the layer, is given by

$$E_{\text{inc}}(z, t) = E_{\text{inc}}^0(z, t) \exp(-\frac{(t - \tau)^2}{\Delta T^2}) \cos(\omega_0 t) \sin(z/v)$$  \hspace{1cm} (1)

Fig. 1. Scattering of electromagnetic plane wave by an air layer (I) in a dielectric medium (II).

Here, $\omega_0$ and $\Delta T$ denote, respectively, the pulse central frequency and width. Also, $\tau = t - t_d - z/c$, where $t_d$ denotes the time at which the peak of the pulse impinges on the $z = 0$ plane and $c = 1/\sqrt{\mu_0 \varepsilon_0}$ is the speed of light in the surrounding dielectric medium. We are interested in finding the yet unknown total electric field $E_z$ expressed as

$$E_z(z, t) = \begin{cases} E_z^I(z, t), & 0 \leq z \leq d \\ E_z^H(z, t), & z < 0, \ z > d \end{cases}$$  \hspace{1cm} (2)

where $E_z^I$ and $E_z^H$ are the total electric fields in the air layer and the surrounding dielectric medium, respectively. The integral equation for the problem under consideration is obtained by first introducing an equivalent polarization current, radiating in free space, defined as

$$J_z^e(z, t) = (z - z_0) \frac{\partial}{\partial t} E_z^e(z, t), \quad 0 \leq z \leq d.$$  \hspace{1cm} (3)

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