Time-Domain Response Simulation of Incident Field Coupling to Transmission Lines

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Abstract—This paper presents an analysis of time-domain electromagnetic (EM) field coupling to transmission lines. The time-domain 3D EM simulation of the field-to-line coupling system is performed using the uniform plane wave excitation defined by the broadband Gaussian pulse. An analytic background is given to justify usage of the simulated time-domain response as an impulse response of the field-to-line coupling system. The simulated impulse response relates the induced voltages at the transmission line terminals to the EM plane wave excitation. By knowing the impulse response it is possible to predict induced terminal voltages for arbitrarily defined time-domain EM fields. This approach is validated by measurements of the EM field coupling in a transverse electromagnetic mode (TEM) cell and on a printed circuit board (PCB) transmission lines. Very good agreement is obtained between the measured results and results obtained by the convolution for various orientations of the transmission lines and various load impedances.

Index Terms—EM field coupling, TEM cell, transmission lines, incident electromagnetic field, transient analysis, measurements, convolution.

I. INTRODUCTION

Important parts of a complete electromagnetic compatibility analysis (EMC) are emission and immunity pre-compliance tests related to the electromagnetic (EM) radiation. The EMC radiation test set-up for integrated circuits usually comprises the printed circuit board (PCB) populated with electronic devices inserted into the wall of a transverse electromagnetic mode (TEM) cell. These tests are usually performed according to standardized procedures, i.e., IEC 61967-2 [1] and IEC 62132-2 [2]. The TEM cell test set-up offers a low-cost alternative to measurements over an open-area test site (OATS) as called for by various standards [3]. In the shielded environment of the TEM cell, the PCB can be exposed to the transverse EM field (immunity) or it can couple to the transverse EM propagating mode (emission). The transverse EM field mimics a uniform plane wave incident field due to some distant radiating source such as radio and television transmitters, radars, lightning, or generators of nuclear electromagnetic pulse (NEMP) and high-power microwave (HPM).

The accurate analysis of the coupling between the PCB traces and an EM field is of great importance. This enables prediction of the induced voltages and currents on the trace which can severely degrade signal integrity and system performance, and potentially even permanently damage sensitive components.

There are number of algorithms developed for estimating the amplitude of the voltage and currents induced on transmission line terminals due to plane EM field illumination [4]–[6]. These algorithms are usually developed for simple transmission lines having a uniform cross-section. Modeling in the frequency domain using a transfer function for the field-to-line coupling system is presented in [7], [8]. The transfer function and the incident field frequency spectrum are used to calculate the spectrum of the induced voltages. A thin-wire model of a microstrip (MS) trace is used to accelerate frequency-domain EM simulations in [9]. The limitation of this method is that the same effective dielectric constant is used for all traces on the PCB. In [10] the prediction of the time-domain response at the transmission line terminals using the impulse response of the field-to-line system is successfully demonstrated. However, there is no analytic explanation as to how to use the simulated time-domain response as the impulse response of the field-to-line coupling system.

In this paper a very efficient finite difference time-domain (FDTD) 3D EM simulator is employed to simulate the impulse response of the field-to-line coupling system for arbitrarily shaped transmission lines. In Section II the analytic background is given for the interpretation of the results obtained from the 3D EM simulator as the impulse response of the field-to-line coupling system. Section III explains the measurement set-up used to validate the proposed approach. Several PCB transmission lines inserted in TEM cell are arbitrarily oriented and terminated in various load impedances for verification.

II. IMPULSE RESPONSE OF FIELD-TO-LINE COUPLING SYSTEM

For a given impulse response $h(t)$ of a linear time-invariant system, the output signal $y(t)$ can be obtained for an arbitrary defined input $x(t)$ by the convolution as

$$
y(t) = \int_{0}^{\infty} h(\tau)x(t - \tau)d\tau.
$$

The plane wave excitation in 3D EM solvers is usually defined by a Gaussian pulse. The time-domain width of the Gaussian pulse is defined by the maximum simulation frequency $f_{\text{max}}$. Fig. 1 presents three different Gaussian pulses defined for maximum frequencies of 25, 50 and 100 GHz. In this example the maximum simulation frequency $f_{\text{max}}$ corresponds to the -20 dB point in the Gaussian pulse frequency-domain spectra $H_{EM}(f)$. For a given maximum...
The higher the maximum simulation frequency \( f_{\text{max}} \) the smaller the width of the Gaussian pulse. For high values of \( f_{\text{max}} \) the plane wave excitation of the field-to-line coupling system can be thought of as Dirac pulse excitation. To consider the voltage monitored at the transmission line terminal as an impulse response of the field-to-line coupling system, the area under the Gaussian pulse should be equal to one. Nevertheless, the area under the Gaussian pulse is not equal to one since the magnitude of the plane wave excitation is defined by the \( |E_{\text{inc}}| \) value. The area \( A \) under the Gaussian pulse for \( |E_{\text{inc}}| = 1 \, \text{V/m} \) for three different maximum simulation frequencies \( f_{\text{max}} \) is presented in Table I.

<table>
<thead>
<tr>
<th>( f_{\text{max}} ) (GHz)</th>
<th>( A ) [V/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>3.42447e-11</td>
</tr>
<tr>
<td>50</td>
<td>1.71223e-11</td>
</tr>
<tr>
<td>100</td>
<td>8.56117e-12</td>
</tr>
</tbody>
</table>

A calculated for chosen Gaussian pulse as \( \hat{h}_{\text{end}} = h_{\text{end}}/A \), resulting in a measurement unit \([\text{V/ms}/\text{V/m}]=1/\text{s}\). By knowing the normalized impulse response of the system \( \hat{h}_{\text{end}} \), the induced voltage at the monitored line end \( u_{\text{end}} \) can be calculated for any type of the disturbance \( x(t) \) by using the discrete version of the convolution integral

\[
u_{\text{end}}[k] = \sum_{i=1}^{\Delta T} \hat{h}_{\text{end}}[i\Delta T] \Delta T \cdot x[i\Delta T - k], \quad (4)
\]

where \( \Delta T \) is the sampling time used for sampling the impulse response and the input signal, and \( i \) is the sample number.

III. VALIDATION

A. Measurement Set-Up

The measurement set-up is presented in Fig. 2. The step signal voltage source (S) is connected to the TEM cell input port. The step signal is generated using the Tektronix SD-24 time-domain transmissiometry/reflectometry head capable of launching the signal with a voltage swing of 250 mV and rise time of 30 ps. The far-end port of the TEM cell is terminated in 50 \( \Omega \).

The TEM cell used in this work is FCC-TEM-JM2 [11]. This TEM cell operates up to 1.65 GHz. The cell has a square opening on the top wall, allowing for the placement of the equipment under test (EUT), which is usually a PCB. For the TEM cell used in this work, the PCB size is 10 cm by 10 cm (opening is 9.1 cm by 9.1 cm). The TEM cell width is 148 mm and the height is 2d = 90 mm. The septum thickness is 1 mm and the width is 102 mm.

The oscilloscope used in this set-up is the Agilent DSA80000B having a bandwidth of 6 GHz and a sampling rate of a 40 GS/s. The oscilloscope has 50 \( \Omega \) inputs. The
amplifier (A) used is the Aronia UBBV2 with 40 dB gain in the frequency range from 1 MHz to 10 GHz.

B. 3D EM Simulation of Impulse Response

The modeling here is performed in a 3D EM simulator [12] using the FDTD algorithm. The absorbing boundary conditions are realized in each direction by 7 perfectly matched layers (PML). The simulations are performed by using CUDA GPU Acceleration (2×GeForce GTS 450) and the time effort for all simulated lines is $\approx 5$ min. for $f_{\text{max}} = 25$ GHz.

Fig. 3 presents the simulation set-up for a conductor-backed coplanar waveguide (CPW-CB). The simulations are performed for two different excitations: endfire and broadside. The endfire excitation is equivalent to the TEM cell measurement set-up when the PCB line position is longitudinal (Fig. 3), while the broadside excitation is equivalent to the case when the PCB line position is transversal (Fig. 2). In both cases the electric $E$-field-to-line coupling is constant ($E$-field vector remains perpendicular to the line), while the magnetic $H$-field-to-line coupling is maximized for the endfire excitation and minimized for the broadside excitation.

![Fig. 3. 3D EM simulation set-up for endfire excitation to the CPW-CB line.](image)

The impulse responses, i.e. the voltage responses at the transmission line terminals, are calculated using lumped ports, denoted as P1 or P2 in Fig. 3. The ports are defined between the line end and the ground plane (GND). In this paper the impulse response is monitored at one 50 $\Omega$ port, while the other port is also 50 $\Omega$, shorted or disconnected (open).

The excitation is performed by a uniform plane wave defined in the time-domain by a Gaussian pulse (2). Several maximum simulation frequencies are chosen to test the validity of the presented approach. The amplitude of the $|E_{\text{inc}}|$ field vector component perpendicular to the line is equal to 1 V/m while the amplitude of the other components is equal to zero.

The electric field $|E_{\text{inc}}|$ in the TEM cell increases proportionally to the TEM cell input voltage $u_{\text{in}}$ as $|E_{\text{inc}}| = u_{\text{in}}/d$, where $d$ is the distance between the septum and the PCB. The simulated impulse response $h_{\text{end}}$ is obtained for a 1 V/m magnitude of the incident electric field $|E_{\text{inc}}|$. In order for these simulation results to hold in the TEM cell excited by 1 V at its input, the normalized impulse response should be divided by the distance $d$ between the septum and the PCB as $h_{\text{end}} = h_{\text{end}}/d$.

C. Test Case: Simple CPW-CB Line

The first test case is a CPW-CB designed on FR-4 substrate having right-angle surface-mount SMA connectors at the terminals. Design parameters of the transmission line are defined according to Fig. 3: $w_1 = 1.4$ mm, $q_1 = 0.3$ mm, $l_1 = 50$ mm, $h_{\text{PCB}} = 1.55$ mm and $\varepsilon_{\text{PCB}} = 4.5$. The 3D EM simulation is performed using a lossless substrate $\tan \delta = 0$ and using perfect electric conductor as the line and ground plane material. The PCB dimensions are $w_{\text{PCB}} = 100$ mm. The near-end and the far-end ports of the MS line (P1 and P2 according to Fig. 3) are terminated in 50 $\Omega$.

![Fig. 4. Comparison of the measurement results and results obtained by convolution for endfire excitation of a simple CPW-CB line at: a) near-end and b) far-end. Line is terminated in 50 $\Omega$. The signal measured at the TEM cell input port is convolved with impulse response obtained for three different simulation frequencies $f_{\text{max}}$.](image)

Fig. 4 presents the comparison of the measurement results and the results obtained by the convolution using three different impulse responses obtained for various max. simulation frequencies $f_{\text{max}}$. The measured step signal at the input port of the TEM cell is convolved with impulse response. Since the cut-off frequency of the TEM cell is equal to 1.65 GHz, the convolution results are filtered in time-domain by a $RC$ low-pass filter having the same cut-off frequency. The reasoning behind the filtering is that in the TEM cell only the TEM mode is efficiently coupled to the transmission line. The presented results show very good agreement regardless the value of the frequency $f_{\text{max}}$. The agreement between the simulation results and the measurement results is very good, in spite of not including the losses in the impulse response simulation set-up.
D. Test Case: Meander MS Line

The second test case is a meander MS line on FR-4 substrate having right-angle through-hole SMA connectors at the terminals. Design parameters of the transmission line are defined according to Fig. 5: \( w_1 = 2.6 \text{ mm} \), \( w_2 = 1.5 \text{ mm} \), \( l_1 = 40 \text{ mm} \), \( l_2 = 10 \text{ mm} \), \( l_3 = 22.6 \text{ mm} \), \( h_{PCB} = 1.55 \text{ mm} \) and \( \varepsilon_{PCB} = 4.5 \). The 3D EM simulation \((f_{max} = 25 \text{ GHz})\) is performed using a lossy substrate \((\varepsilon = 5.8e7 \text{ S/m})\) as the line and ground plane material. The PCB dimensions are \( w_{PCB} = l_{PCB} = 100 \text{ mm} \).

Fig. 5. 3D EM simulation set-up for a meander MS line. Two types of excitation are taken into account: (1) endfire and (2) broadside.

Fig. 6 presents the comparison of the measurement results and the results obtained by the convolution for the meander MS line. For two different line orientations as well as for different loading conditions the agreement between presented results is very good. The disagreement between the measurement and simulation results is attributed to the SMA connector-to-transmission line transition. This transition introduces additional delay for the measured results compared to the simulation results. In addition, this transition also represents a discontinuity in terms of characteristic impedance and introduces ringing in the measured response.

IV. CONCLUSION

The impulse response of the field-to-line coupling system can be obtained in a 3D EM simulator. The acceleration algorithms available for FDTD solver enable efficient calculation of the impulse response for complex shaped lossy transmission lines. This approach is verified by measurements performed in a TEM cell. The agreement between the measurements and the simulation results is very good. This approach enables efficient calculation of the time-domain response for an arbitrary shaped transmission line as well as for a user-defined disturbance. Future work will try to assess limitation of this approach in extended frequency range where non-linear effects of a transmission line play important role.

REFERENCES


