Electromagnetic Field Calculation in the Time-Domain at Points outside the TLM Workspace

Nebojša Dončov, Bratislav Milovanović

Abstract – **In this paper, an approach for electromagnetic field calculation in the time-domain at points outside the defined numerical workspace is presented. This approach is primarily intended for electromagnetic compatibility problems analysis and allows for fast and accurate field calculation without resorting to discrete mesh which encloses these points. It is based on integration over Huygens surface surrounding all electromagnetic structures within the workspace. Approach is implemented in TLM numerical algorithm by means of a conveyor belt used for the introduction of the time delay in the near-to-near transform. Accuracy and efficiency of the approach are illustrated on the appropriate examples.**

Keywords – **electromagnetic compatibility, TLM, Huygens surface, time delay, output outside workspace**

I. INTRODUCTION

Electromagnetic compatibility (EMC) is the branch of science and engineering concerned with the design and operation of equipment in a manner which makes them immune to certain amounts of electromagnetic (EM) interference, while at the same time keeping equipment-generated interference within specific limits [1]. The scope of EMC is thus very wide as it encompasses virtually all equipment powered by electrical supplies. In recent years, the rapid increase in the use of radio communications, digital systems, fast processors and the introduction of new design practices have brought EMC to the forefront of advanced design.

How practical modern systems exceed in complexity anything that can be solved analytically or using approximate techniques, numerical computer-based models are the only alternative to study trends in EMC design and to understand the behaviour of systems. Differential numerical techniques in the time-domain, such as Finite-Difference Time-Domain (FD-TD) [2] and Transmission-Line Matrix (TLM) [3], are well established for solving a number of EMC problems over a wide frequency range. These methods, due to their characteristics and the development of powerful computer stations, offer a significant extension of the range of EMC problems that can be tackled.

However, there are still numerous practical EMC problems where these techniques, even with the use of computer stations of remarkable memory and run-time performances, are incapable to allow for their fast and correct modelling. The examples are geometrically small but electrically important features (such as thin wires, slots, air-vents, etc) in an otherwise large modelling space. For their description, extremely fine mesh is required which can result in a prohibitively large number of cells and large number of time steps. In recent years, enhancements to TLM technique in the form of so called sub-cell or compact models have been developed to allow for an efficient simulation of these structures [4-6]. These models take into account the EM presence of fine details without resorting to extremely fine mesh around them.

Level of equipment-generated interference is one of the key concerns in EMC design. Thus a complete analysis of EMC problems requires calculation of EM field response at points far away from the EM structures generating this response. Again, large number of cells is required to cover the distance between equipment and outputs, which can exceed the dimensions of EM structures by one order of magnitude or more. This leads to time consuming and inefficient EMC simulation even with the use of developed compact models.

The technique of EM field calculation at points located at large distances from the radiating EM structures, without defining discrete numerical mesh up to these points, is developed and presented in this paper. It is based on Love's equivalence principle [7,8] and requires definition of so-called Huygens closed surface within the workspace surrounding all EM structures of analyzed EMC problem. Integration over the Huygens surface, divided into elemental patches whose cross-section is determined by the resolution of applied numerical mesh, at every time step allows for calculating the time-domain EM field at points outside the numerical workspace. The time delay in near-to-near transform is introduced by means of a conveyor belt. Proposed scheme is implemented in TLM numerical algorithm and verified on appropriate examples. Compared to the conventional simulation, huge saving in simulation run-time can be achieved.

II. LOVE'S EQUIVALENCE PRINCIPLE

The surface equivalence theorem is a principle by which actual sources, such as an antenna and transmitter, are replaced by equivalent sources. The fictitious sources are said to be equivalent within a region because they produce within that region the same field as the actual sources. According to this principle, the fields outside an imaginary closed surface are obtained by placing, over the closed surface, suitable electric and magnetic current densities that satisfy the boundary conditions. The current densities are selected so that the fields inside the closed surface are zero and outside are equal to the radiation produced by the actual sources. Thus this technique can be used to obtain the fields radiated outside

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a closed surface by sources enclosed within it. The formulation is exact but requires integration over the closed surface.

The surface equivalent theorem can be illustrated by considering an actual radiating source, which is represented electrically by current densities J_1 and M_1, as shown in Fig.1. The source radiates fields E_1 and H_1 everywhere. In order to develop a method that will yield the fields outside a closed surface as actual sources, a closed surface S has to be chosen (dashed lines in Fig.1a) which encloses the current densities J_1 and M_1. The volume within S is denoted by V_1 and outside S by V_2. The primary task is to replace the original problem shown in Fig.1a with an equivalent that will yield the same field E_1 and H_1 outside S (within V_2)

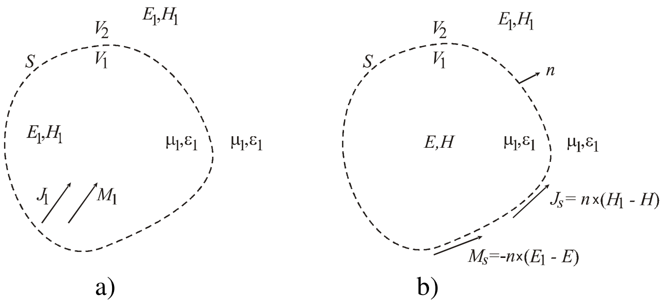


Fig. 1. a) Actual and b) equivalent problem models

An equivalent problem to Fig.1a is shown in Fig1.b. The original sources J_1 and M_1 are removed, and one can assume that there exist fields E and H inside S and fields E_1 and H_1 outside S. For these fields to exist within and outside S, they must satisfy the boundary conditions on the tangential electric and magnetic field components. Thus on the imaginary surface S the following equivalent sources must exist:

$$J_s = n\times(H_1 - H) \tag{1}$$

$$M_s = -n\times(E_1 - E) \tag{2}$$

which radiate into an unbounded space (same medium everywhere). The current densities J_s and M_s are said to be equivalent only within V_2, because they will produce the original fields (E_1 and H_1) only outside S. A fields (E and H) different from the original (E_1 and H_1) will result within V_1. Since the fields (E and H) within S, which is not the region of interest, can be anything, it can be assumed that they are zero. Then the equivalent current densities are equal to:

$$J_s = n\times(H_1 - H)\big|_{H=0} = n\times H_1 \tag{3}$$

$$M_s = -n\times(E_1 - E)\big|_{E=0} = -n\times E_1 \tag{4}$$

This form of the field equivalence principle is known as Love's equivalence principle [7,8]. Since the current densities J_s and M_s radiate in an unbounded medium that is, have the medium (μ_1,ε_1) everywhere, they can be used in conjunction with the Eqs.(5) and (6) to find the fields everywhere:

$$E_1 = -j\frac{1}{\omega\mu_1\varepsilon_1}\nabla(\nabla\cdot A) - j\omega A - \frac{1}{\varepsilon_1}\nabla\times F \tag{5}$$

$$H_1 = -j\frac{1}{\omega\mu_1\varepsilon_1}\nabla(\nabla\cdot F) - j\omega F + \frac{1}{\mu_1}\nabla\times A \tag{6}$$

where A and F are vector magnatic and electric potential, respectively, that can be expressed through electric and magnetic surface currents as [8]:

$$A = \frac{\mu_1}{4\pi}\int_S J_s \frac{e^{-jkR}}{R}dS', \quad F = \frac{\varepsilon_1}{4\pi}\int_S M_s \frac{e^{-jkR}}{R}dS' \tag{7}$$

III. Near-to-near Transform

The contribution of an elemental patch of the Huygens surface to EM field at a point removed from it by the vector R can be found in the time-domain from Eqs.(5-7) as:

$$\Delta E(t + R/c) = \frac{\Delta S}{4\pi R\cdot R}\left(\Delta E_{rad}(t) + \Delta E_{ind}(t) + \Delta E_{stat}(t)\right) \tag{8}$$

$$\Delta H(t + R/c) = \frac{\Delta S}{4\pi R\cdot R}\left(\Delta H_{rad}(t) + \Delta H_{ind}(t) + \Delta H_{stat}(t)\right) \tag{9}$$

where ΔS is the area of the elemental patch determined by TLM node. As it can be seen the signal from each surface patch consists of a differential radiation term (ΔE_{rad} and ΔH_{rad}), a direct induction term (ΔE_{ind} and ΔH_{ind}) and an integral static field term (ΔE_{stat} and ΔH_{stat}) that can be expressed in rectangular coordinate system as:

$$\Delta E_{rad}(t) = \frac{|R|}{c}\frac{d}{dt}\left(Z_0((J_s\cdot R_{ort})\cdot R_{ort} - J_s) - M_s\times R_{ort}\right) \tag{10}$$

$$\Delta E_{ind}(t) = Z_0(3(J_s\cdot R_{ort})\cdot R_{ort} - J_s) - M_s\times R_{ort} \tag{11}$$

$$\Delta E_{stat}(t) = \frac{c}{|R|}\int Z_0(3(J_s\cdot R_{ort})\cdot R_{ort} - J_s)dt \tag{12}$$

$$\Delta H_{rad}(t) = \frac{|R|}{c}\frac{d}{dt}\left(Y_0((M_s\cdot R_{ort})\cdot R_{ort} - M_s) + J_s\times R_{ort}\right) \tag{13}$$

$$\Delta H_{ind}(t) = Y_0(3(M_s\cdot R_{ort})\cdot R_{ort} - M_s) + J_s\times R_{ort} \tag{14}$$

$$\Delta H_{stat}(t) = \frac{c}{R}\int Y_0(3(M_s\cdot R_{ort})\cdot R_{ort} - M_s)dt \tag{15}$$

where Z_0 is an intrinsic impedance of free space ($Y_0 = 1/Z_0$), R_{ort} *is* unit vector ($R_{ort} = R/|R|$) and J_s and M_s are the equivalent electric and magnetic current densities, respectively.

The time delay R/c in the near-to-near transform is introduced by means of a conveyor belt shown in Fig.2. Each output point is at the delivery end of its own conveyor which carries a time-domain signal towards it at the speed of light. In order to introduce a delay R/c into a signal, the signal is dropped onto the conveyor at the distance R upstream of the output point.

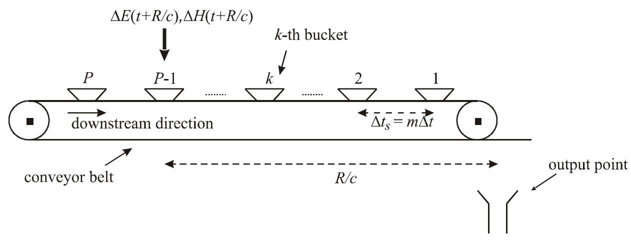


Fig. 2. Conveyor belt for one output point

The conveyors are not continuous but consist of buckets spaced one time sample, Δt_s, apart. Time sample depends on highest frequency of interest for EM response analysis and in general can be expressed as integer number, m, of used time step in TLM simulation, Δt ($\Delta t_s=m\Delta t$). If a signal is dropped onto the conveyor belt at time, $i\Delta t$, (i=1,2,...,I_{max}, where I_{max} is maximum number of iteration of simulation in the time-domain) when a bucket is not passing the loading point in question, then the signal falls between buckets and is lost. The conveyor belt and buckets on it advance with step Δt towards output point (downstream direction). The time delay R/c is introduced in the way that signal corresponding to the appropriate elemental patch of Huygens surface at distance R from the output point is dropped onto appropriate place at conveyor belt ($\Delta E(t+R/c)$ and $\Delta H(t+R/c)$, given by Eqs.(8-15)). The total length of a conveyor is determined by the maximum required delay, i.e. by the distance between the output point and the most remote patch of the Huygens surface and it can be calculated as:

$$P_{\max} = 1 + \mathrm{int}\left(R_{\max} / c / \Delta t\right) \tag{16}$$

a) Differential radiation term

The differential term is generated by dropping an up-down pulse onto the conveyor. Specifically, if a signal of $dv(t)/dt$ is required, then at each time step a value of $+v/dt$ is dropped onto the conveyor at one point, and a value of $-v/dt$ is dropped at a point one time step upstream of the first. At most one of these values will actually land in a bucket. The up-pulse at one time step will always land at the same place on the conveyor as the down-pulse at the previous time step (the conveyor having advanced) so that bucket will catch: $(+v(t+\Delta t)-v(t))/\Delta t$. Because the desired delay may not be an exact half-integral number of time steps, the loading points for the up- and down- pulses may be misaligned with the conveyor. To handle this, each of the up- and down- pulses may be shared between two adjacent locations on the conveyor, so that the entire up-down pulse is spread over a three time steps length (at least 2/3 of this falling between buckets). If the desired delay requires a loading point, n time steps from the delivery end of the conveyor, and if N=nint(n) is the nearest integer value, then weightings are:

$$\mathrm{drop}[N\text{-}1] = \left(N + 1/2 - n\right)v(t)/\Delta t$$
$$\mathrm{drop}[N] = 2\left(n - N\right)v(t)/\Delta t$$
$$\mathrm{drop}[N+1] = \left(N - 1/2 - n\right)v(t)/\Delta t$$

b) Direct term

The value for the direct induction term is simply dropped onto the conveyor at the desired point. However, since this point may not a non-integral number of time steps from the output point, the value may need to be shared between two adjacent locations on the conveyor. If the desired delay requires a loading point n time steps from the delivery end of the conveyor, and $N1$ and $N2$ are consecutive integers bracketing n, then weightings are:

$$\mathrm{drop}[N1] = \left(N2 - n\right)v(t)$$
$$\mathrm{drop}[N2] = \left(n - N1\right)v(t)$$

At most one of these values will actually land in a bucket.

c) Integral term

The integration for the static-field term is achieved by dropping the integrand (times Δt) onto all locations on the conveyor upstream of the desired delay point (most of these being between buckets). To achieve the effect of a conveyor that extends upstream indefinitely, the most-upstream bucket is initialized with the contents of the previously most-upstream bucket every time the conveyor advances by a whole time sample. Care must be taken that the most-upstream bucket is sufficiently far upstream to avoid contamination from the differential or direct terms emanating from the remotest part of the Huygens surface.

If the desired delay is n time steps, and n is not a half-integral number, then a weighting of

$$\mathrm{drop}[N] = \left(N + 1/2 - n\right)v(t)\Delta t$$

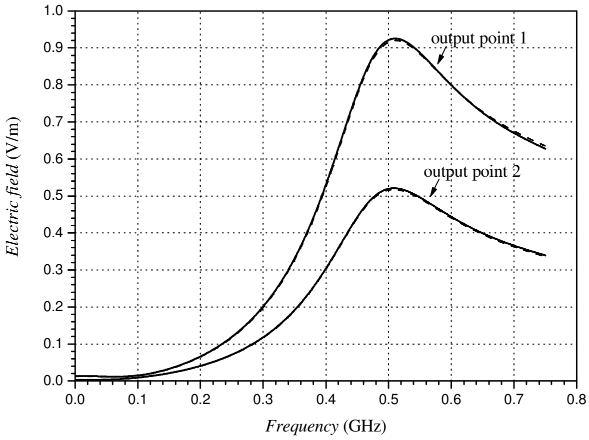
may be applied to the nearest location N=nint(n) (should a bucket be passing this point at the time), with the full value $v(t)\Delta t$ being applied to all upstream locations.

IV. Numerical Analysis

The accuracy of scheme for calculating the time-domain EM field at points outside the TLM workspace is verified on the simple example of dipole antenna radiating in free space. Dipole antenna is represented as straight wire conductor of radius r=0.5 cm and length l=28 cm. Compact wire model [4] is used for wire modelling. Real voltage generator, 1V and 50 Ω, is placed at the centre of the wire. EM field time-domain response at two output points placed around dipole antenna is calculated by one TLM simulation and two different approaches: a) enclosing the output points by numerical mesh of TLM nodes and using conventional TLM algorithm of scattering and connection [2]; and b) applying integration over a Huygens surface enclosing the dipole antenna. After using discrete Fourier transformation, the EM field at these points in the frequency-domain is shown in Fig. 3. It can be noticed a good agreement between the results obtained by these two approaches.

The efficiency of proposed scheme is illustrated on the realistic EMC example in the form of rectangular shielding enclosure (Fig.4). The enclosure was constructed of five pieces of 0.635 cm thick aluminum, and one plate of 0.05 cm thick aluminum (face containing the slot). The inside dimensions of the enclosure were 22 cm × 14 cm × 30 cm. The feed probe was represented as a wire conductor of 0.16 cm diameter terminated at the bottom of the cavity by 47 Ω resistor. Simple voltage source, 1mV with 50 Ω resistance, was incorporated into the wire at the top of the cavity. Slot length and width were 12 cm and 0.1 cm, respectively. Compact wire [4] and slot model [5] were used to model wire conductor and slot structure in order to avoid the need of TLM mesh with extremely high resolution. The choice of geometry, excitation and output was governed by experimental arrangements used in [9].

Huygens virtual surface, completely surrounding the TLM model of the enclosure, is located at the distance of one TLM node from the enclosure. The external boundaries of TLM mesh are placed around the enclosure at the distance greater than 30% of the largest dimension of the enclosure, which is still far away from the required output point. The results for far zone electric field at 3 m away from the face of enclosure containing slot, obtained by using the proposed scheme, are compared with the experimental results [9] and shown in Fig.5. An excellent agreement between these two results can be observed. In addition huge saving in the computer resources, compared to conventional TLM, is achieved with accuracy acceptable for most EMC applications.



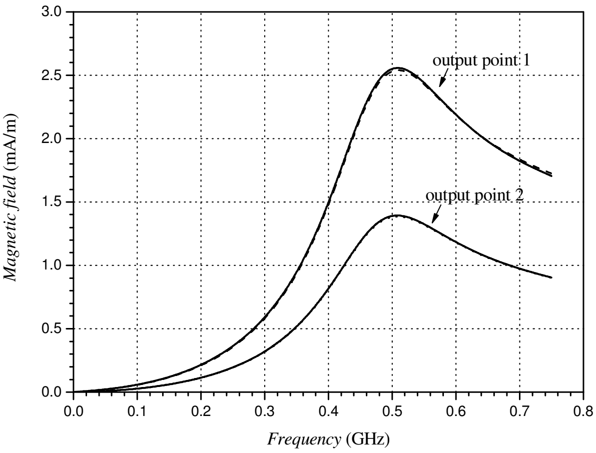


Fig. 3. EM field at output points obtained by: a) conventional TLM (dotted line), b) proposed scheme (solid line)

V. CONCLUSION

This paper describes an efficient scheme for calculating the time-domain EM field at points outside the TLM workspace. It is primarily indented for EMC applications. The proposed scheme is based on integration over a Huygens surface within the defined workspace using the calculated equivalent electric and magnetic surface currents. The effect of time delay in signal propagation from elemental patches of Huygens surface to output points is realized through appropriate conveyor belts. The scheme is general and it can be implemented into other differential numerical techniques in the time-domain such as FD-TD method. The efficiency of this approach is illustrated on the appropriate examples.

Because the integration over the Huygens surface involves a significant amount of computation, it may be worthwhile attempting to reduce the integration frequency from once every time step to once every time sample. Even if the computational burden for a single output point proves acceptable, it can be easily be made unacceptable by specifying sufficiently many output points. The modification of integration frequency that incurs the cost of extra storage, but has an advantage that this cost is fixed and it does not increase with the number of output points will be presented in future papers.

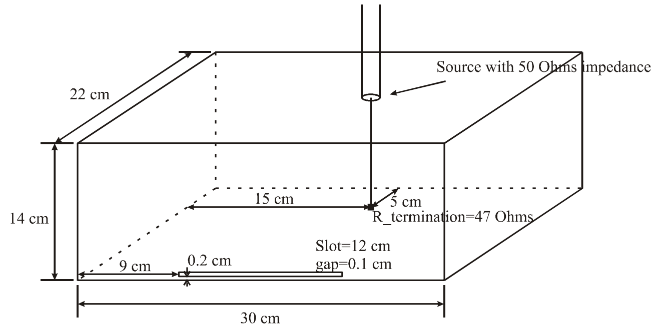


Fig. 4. Rectangular test enclosure

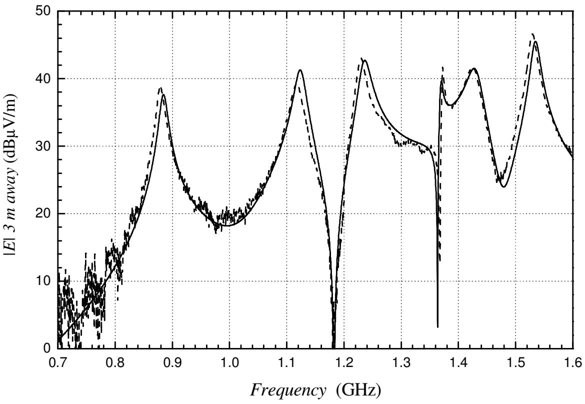


Fig. 5. Radiated electric field at 3 m away from the enclosure: a) measurements (dotted line), b) proposed scheme (solid line)

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