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A Pivotal Element for Accurate Simulations

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Excitation in Time-Domain Analyses: A Pivotal Element for Accurate Simulations

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***Abstract* — A simple and efficacious modality of introducing causal excitations in CST Studio Suite® time-domain simulations is described. It makes use of (concatenations of) so-called discrete ports that are shown to accurately substitute Dirichlet boundary conditions and replicate dipole excitations. Numerical experiments cogently demonstrate the approach's exceptional replication accuracy and computational effectiveness.**

I. Introduction

Commercial software tools are presently a pervasive presence in antenna engineering (AE), with numerical validations via such instruments becoming an almost implicit requirement for publishing results. Among them, CST Studio Suite® (CST Studio) and Ansys HFSS (HFSS) are the *de facto* standard validation instruments, with the use of other software tools being confined to niche areas. These two packages play such a dominant role that even properly argued (semi-)analytical frameworks are often accepted only inasmuch as they are backed by some numerical validation via one of them.

This paper will concentrate on some technical details concerning the time-domain (TD) electromagnetic (EM) analysis. The discussion will be restricted to CST Studio simulations but the inferred conclusions can be extended to HFSS. After motivating the need for this study and introducing some prerequisites, the account will examine two canonical problems with (semi-)analytical solutions: (i) the radiation from a wide slot in a perfectly electric conducting (PEC) wall with a dielectric overlay (the "wide slot" problem) [1]; (ii) the radiation from a magnetic dipole in free space (for which the treatment in [2] will be used as a baseline) and in a layered media [3]. The paper will end by drawing conclusions.

II. Motivation and prerequisites

With more than two decades since its commercial introduction, CST Studio has garnered a huge experience in its use. In particular, the package has demonstrated its remarkable effectiveness in AE applications, with extremely complex simulations being presently within reach. Nevertheless, these authors noticed that AE simulations are primarily focussing on frequency-domain (FD) explorations. Note that, although quite frequently the relevant simulations are effectuated with the TD version of the package, the end results are still of the FD variety. At variance with this, truly TD studies, based on TD arguments and aiming explicitly at TD results, are comparatively (much) less frequent.

TD simulations require, in general, more care. To begin with, TD explorations must ensure *strict causality* (see the argument in [4]). Surprisingly, standard TD excitations in commercial software, in general, and in CST Studio, in particular, are derived from the Gaussian pulse shape which is *non-causal*! Furthermore, subtle details in the signatures often require careful meshing and time sampling. Thirdly, certain boundary conditions (BCs) setups are not effective. For example, periodic BCs are extremely popular in FD, but make less sense in TD experiments. Conversely, TD studies also offer specific opportunities, *e.g.* performing time-gated simulations using time-windowed excitations in conjunction with sufficiently large domains of computation (see [5]) – an approach emulating genuinely reflectionless EM radiation.

A pivotal source of concern in TD EM simulations refers to excitation. Even when resorting to strictly causal pulse-shapes, CST Studio raises some (im)practicality issues: (i) the standard Dirichlet and Neumann BCs are not available and (ii) building volume or surface current sources is cumbersome, especially in TD. One particularly inconvenient situation encountered by these authors was implementing dipole-type excitations. In this respect, attempting to implement a magnetic dipole via a current source fed, PEC loop entails excessive meshing (see Section IV). This spatial meshing results, in turn, in extremely small time steps, as required by the Courant-Friedrichs-Lewy condition [6] – such a temporal discretisation is often an overkill for the problem at hand. As it will be clearly demonstrated, these limitations can be effectively sidestepped by making use of a facility that is readily available in CST Studio, *the discrete ports*.

Position is specified in all examined configurations with respect to a Cartesian reference frame with origin O and three mutually orthogonal unit vectors $\{\boldsymbol{i}_x, \boldsymbol{i}_y, \boldsymbol{i}_z\}$. The time coordinate is t, and t' is any of its normalised counterparts. Position vectors are denoted as $\boldsymbol{r} = x\boldsymbol{i}_x + y\boldsymbol{i}_y + z\boldsymbol{i}_z$. The infinite embedding is taken to be free space with permittivity ε_0, permeability μ_0, wavespeed $c_0 = (\varepsilon_0\mu_0)^{-½}$ and impedance $Z_0 = (\mu_0/\varepsilon_0)^{½}$. Non-free-space domains are characterised by their relative permittivity ε_{r}, relative permeability μ_{r} and, possibly, conductivity σ. The experiments will make use of the power-exponential (PE) [4] and windowed-power (WP) [5] families of pulses, with $\nu \geqslant 2$ being their integer raising power, $t_{\mathrm{r}} > 0$ their pulse rise-time and $t_{\mathrm{w}} > 0$ their (conventional) pulse width. The studies will involve comparisons between components of some *reference* electric $\boldsymbol{E}(\boldsymbol{r},t)$ or magnetic $\boldsymbol{H}(\boldsymbol{r},t)$ field signatures and their corresponding *CST Studio (computed)* counterparts, the reference signatures being evaluated via (semi-)analytical strategies. All plots will be constructed for normalised values, with the reference values providing the normalisation quantity and the CST Studio signatures being aligned to the reference such that the maximum absolute values are equal. Note that the deviation between the maximum absolute values of the *un-aligned* simulated and reference signatures was always lower than 5%! The time coordinate will also be normalised and the two types of signatures will be time-aligned within the interval $\mathcal{T}$ over which both of them are available (with t' of the reference signatures being taken as the leading quantity). The deviation between signatures will be evaluated based on the *global* replication error

$$\mathrm{Err}_{\%} = \frac{\displaystyle\int_{\mathcal{T}} |V_{\mathrm{norm}}(t') - \tilde{V}_{\mathrm{norm}}(t')| \mathrm{d}t'}{\displaystyle\int_{\mathcal{T}} |V_{\mathrm{norm}}(t')| \mathrm{d}t'} \times 100 \qquad (1)$$

in which $V_{\mathrm{norm}}(t')$ denotes the reference signature and $\tilde{V}_{\mathrm{norm}}(t')$ the CST Studio replicated one.

III. Study-Case 1: The "Wide Slot" Problem

This problem was discussed in [1]. The examined configuration (see Fig. 1) consists of a dielectric slab $\mathcal{D}_1$ of thickness d on top of a PEC ground plane, and an infinitely extended free-space, half-space $\mathcal{D}_0$. The configuration is excited via a slot in the PEC along which $E_x(t)$ has a prescribed, PE-pulse-shaped temporal behaviour. Due to the plane-parallel invariance in the y-direction, the entailed EM problem is two-dimensional (2D) and lends itself to a semi-analytic solution via the Cagniard-de Hoop (**C-dH**) method [7].

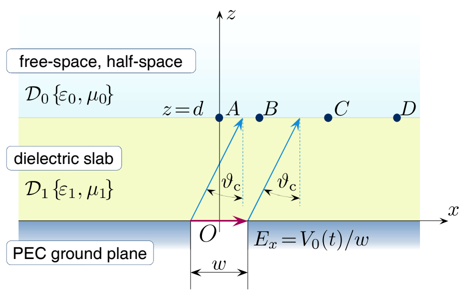

Fig. 1. Configuration concerning the "wide slot" problem. Location of the points: A $\leftrightarrow x = 0$, B $\leftrightarrow x = d$, C $\leftrightarrow x = 3d$ and D $\leftrightarrow x = 5d$.

Despite its simplicity, simulating in CST Studio the configuration in Fig. 1 is not trivial. Since Dirichlet BCs are not available, one may consider using a parallel-plate waveguide excitation. However, this choice is incongruent with the model since a waveguide has a nonuniform field distribution at its aperture that even features corner singularities. Another limitation is that a waveguide has a penetrable, impedance-type aperture, whereas the examined model leaves an impenetrable PEC wall after the exciting pulse was radiated. Alternatively, one may consider placing a magnetic current sheet above the PEC, as routinely done in FD analyses. However, a TD magnetic current sheet cannot be implemented in CST Studio.

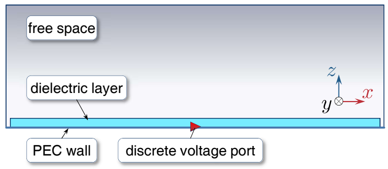

Fig. 2. CST Studio domain of computation for the "wide slot" problem.

This problem was solved by placing a discrete voltage port at a very small height above the PEC (see Fig. 2). The domain of computation was chosen as extremely thin in the y-direction, with magnetic-wall BCs on the y = constant faces ensuring the 2D character of the field. Comparisons between the reference values evaluated via the strategy in [1] and the CST Studio replicated ones are shown in Figs. 3 and 4 for two points in Fig. 1. The reference signatures correspond to the normalised $E_x w/V_{\mathrm{max}}$ and $Z_0 H_y w/V_{\mathrm{max}}$ field quantities and $t' = c_0 t/d$. The PE pulse has $\nu = 2$ and its rise time t_{r} is selected such that $c_0 t_{\mathrm{w}}/d = 0.9236$. The plots demonstrate the excellent replication of even the small details in the examined signatures. The global errors calculated via (1) for all points Fig. 1 are given in Table 1, the largest recorded error being of 8.5%.

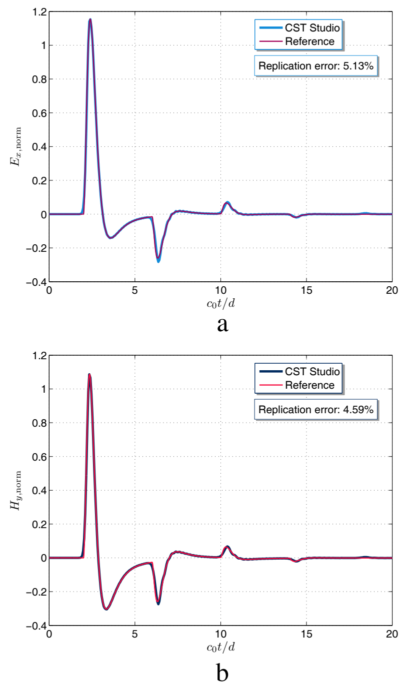

Fig. 3. Comparison of the reference and CST Studio simulated signatures at point A in Fig. 1. (a) normalised E_x; (b) normalised H_y.

IV. Study-Case 2: A Radiating Magnetic Dipole

The second study-case concerns the EM field emitted by a small, conducting, current-carrying loop in (i) free space and (ii) a layered configuration. The presented numerical

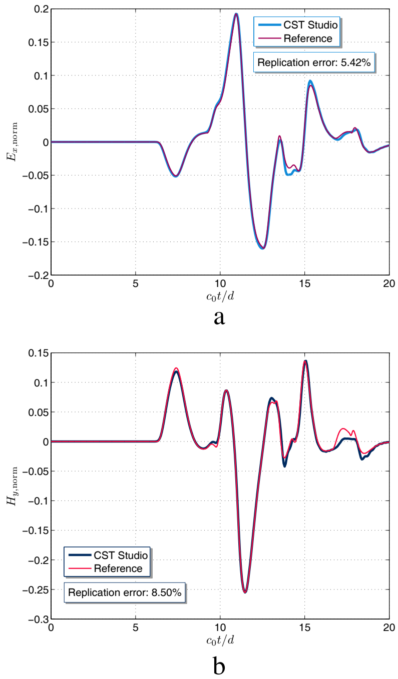

Fig. 4. Comparison of the reference and CST Studio simulated signatures at point D in Fig. 1. (a) normalised E_x; (b) normalised H_y.

Table 1. Replication errors in the case of the "wide slot" problem.

Field point (see Fig. 1)	Replication error for $E_{x,\mathrm{norm}}$	Replication error for $H_{y,\mathrm{norm}}$
A	5.13%	4.59%
B	2.63%	3.38%
C	5.58%	5.46%
D	5.42%	8.50%

experiments make use of the time-differentiated, windowed-power (∂_tWP) pulse of raising power $\nu = 5$ and time-rise $t_\mathrm{r} = 0.1$ ns (see [5] for the relevant definitions and examples of time- and frequency-domain plots). Note that the pulse width of this pulse shape is $t_\mathrm{w} = 2t_\mathrm{r}$.

A. Radiating magnetic dipole in free space

The case of the EM field emitted by a small, conducting, current-carrying loop in free space is firstly examined. This radiation was elaborately discussed in [8, Section 26.10], the reference values needed for the present paper being obtained via the corresponding expressions in [4].

The study concerns a small loop antenna $\mathcal{L}^\mathrm{T}$ of reference centre at the origin of the reference system (see Fig. 5). Its oriented area is $\boldsymbol{A}^\mathrm{T} = A^\mathrm{T}\boldsymbol{i}_z$ and it carries a current $i(t)$ whose temporal behaviour is a ∂_tWP pulse. In view of the configuration's rotational symmetry, it suffices to study the problem in the $\{x > 0, y = 0\}$ half-plane. In this plane, E_y, H_x and H_z are the sole non-zero quantities – only E_y and H_z will be henceforth examined.

This configuration was firstly simulated in CST Studio by constructing a circular PEC loop whose length was significantly shorter than the pulses spatial extent $c_0 t_\mathrm{w}$. The

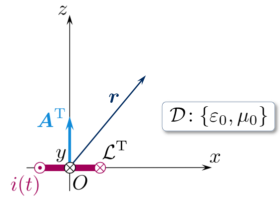

Fig. 5. Configuration concerning the dipole radiation in free space.

wire's diameter d_w had to be largely inferior to the loop's radius R. The loop was fed via a discrete current port located inside a gap of width $w \ll d_\mathrm{w}$. Diametrically opposite, the field had to be sampled at locations $\boldsymbol{r}$ with $|\boldsymbol{r}| \gg R_\mathcal{L}$ for justifying the assumption of the loop being a magnetic dipole. Furthermore, the domain of computation was large enough for allowing a reflectionless time-gated simulation at the field point. It is then evident that this approach required defining and meshing elements with relative sizes stretching several orders of magnitude. While the computational results were reasonable, they were clearly impeded upon by: (i) the non-negligible dimensions of the loop; (ii) the spurious scattering on the PEC loop; (iii) above all, the distinctly poor aspect ratio of many cells in the vastly non-uniform mesh.

These drawbacks were all resolved by replacing the loop by a concatenation of 4 discrete, synchronous current ports forming a square of size $2R$. Since no meshing of the wire and of the gap was needed, the aspect ratio of the mesh improved greatly. The reference and CST Studio simulated signatures at the point $\boldsymbol{r} = \boldsymbol{i}_x + 4\boldsymbol{i}_z$ (mm) are compared in Fig. 6 – the signatures are in excellent agreement, as also confirmed by the global representation errors. Note that the reference E_x was normalised to its maximum absolute value, whereas the reference H_z was normalised to the maximum total H-field magnitude. Additionally, a smoothing was applied to the CST Studio signatures for eliminating some small high-frequency oscillations superposed on the genuine traces.

B. Radiating magnetic dipole in a layered configuration

Secondly, a layered configuration that was dealt with via the **C-dH** method in [3] is examined. This configuration is shown in Fig. 7 and consists of a magnetic dipole enclosed in a lossless SiO_2 dielectric layer located on top of a lossy SiO_2 substrate. Such a structure mimics a CMOS integrated loop antenna fabricated via the process described in [9], the intervening medium parameters being given in Table 2.

Table 2. Properties of the media in the layered CMOS configuration.

Domain	Relative permittivity ε_r	Relative permeability μ_r	Conductivity σ (Sm^{-1})
$\mathcal{D}_1$	1	1	0
$\mathcal{D}_2$	3.9	1	0
$\mathcal{D}_3$	11.7	1	10^{-3}

The radiating dipole was implemented again as a concatenation of 4 discrete, synchronous current sources forming a square. The reference and CST Studio simulated signatures

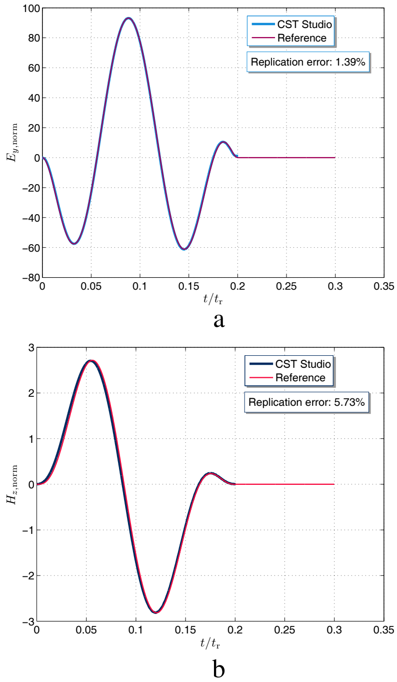

Fig. 6. Comparison of the reference and CST Studio simulated signatures at the point $\boldsymbol{r} = \boldsymbol{i}_x + 4\boldsymbol{i}_z$ (mm). (a) normalised E_x; (b) normalised H_y.

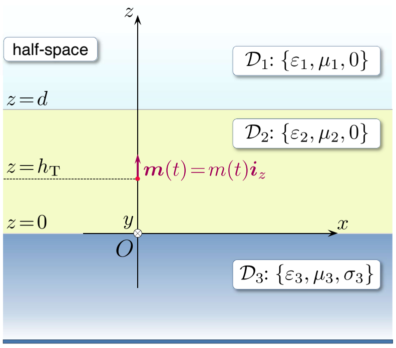

Fig. 7. The CMOS integrated loop antenna configuration. The loop antenna is represented via its pertaining magnetic moment $\boldsymbol{m}(t) = i(t)A^{\mathrm{T}}\boldsymbol{i}_z$, with $i(t)$ being the feeding electric current and A^{T} the loop's area.

at the point $\boldsymbol{r} = \boldsymbol{i}_x + 4\boldsymbol{i}_z$ (mm) are compared in Fig. 8. Apart from some deviations at later times that may be attributed to meshing and, possibly, some spurious reflections from the boundary, the agreement is quite good. Note that the reference values were normalised as in Section IV-A and a smoothing of the CST Studio signatures was again applied.

V. Conclusions

Implementing causal excitations in CST Studio Suite® TD simulations by means of (concatenations of) discrete ports was demonstrated. The efficacy of this strategy was demonstrated by solving 3 EM problems with (semi-)analytical solutions. The advocated solution allows obtaining a very high replication accuracy while faultlessly reproducing the original model without excessive computational costs.

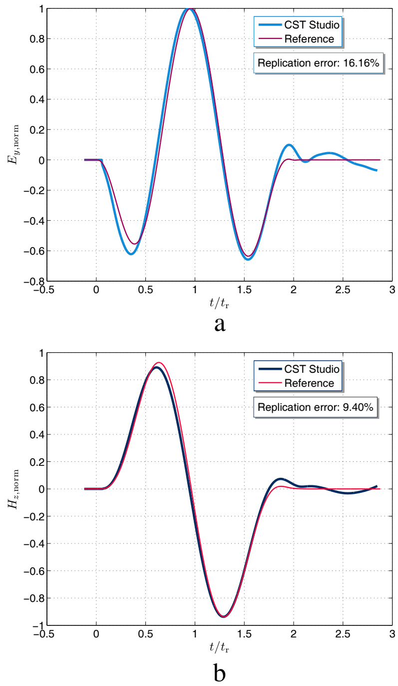

Fig. 8. Comparison of the reference and CST Studio simulated signatures at the point $\boldsymbol{r} = \boldsymbol{i}_x + 4\boldsymbol{i}_z$ (mm). (a) normalised E_x; (b) normalised H_y.

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