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FAST TIME DOMAIN INTEGRAL EQUATION BASED ELECTROMAGNETIC ANALYSIS: A MATURING TECHNOLOGY

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Abstract. The analysis of transient scattering from perfectly conducting as well as potentially inhomogeneous penetrable bodies often is effected using marching on in time based time domain integral equation methods. This paper reviews the state of the art in the field, highlighting recent advances that address not only their stability and computational efficiency, but also their convergence and hybridization/interoperability with other solvers. The potential of this maturing technology is demonstrated via its application to several challenging electromagnetic compatibility and interference problems.

1 INTRODUCTION

To ensure the interoperability of modern broadband and integrated navigation and communication systems (Fig. 1), engineers are in need of analysis tools capable of tracking electromagnetic transients in electrically large and complex, multiscale and potentially nonlinearly loaded environments. In this context, marching on in time (MOT)-based time domain integral equation (TDIE) solvers provide an increasingly appealing alternative to finite difference based simulation engines. Indeed, recent algorithmic advances have rendered these solvers both computationally stable and applicable to the analysis of not only perfect electrically conducting, but also penetrable/lossy structures comprising homogeneous and inhomogeneous volumes with wire attachments [1-6]. Moreover, the computational efficiency of MOT-based TDIE solvers has increased due to their acceleration by plane wave time domain [7] and time domain adaptive integral [8] algorithms capable of rapidly evaluating transient fields due to wideband source constellations. Finally, these solvers have been hybridized with a variety of tools [9-12] aimed at the reduced (order) modeling of electronic and electromagnetic subsystems, e.g., circuits, electronic components and printed circuit boards, and cables. These advances have led fast TDIE solver technology to approach a stage of maturity permitting its widespread application to complex real-world scattering, radiation, and guidance problems. This paper summarizes key recent advances in the field and demonstrates the technology's applicability to a host of real-world electromagnetic compatibility and interference (EMC/EMI) problems. Because of space constraints, the review is heavily biased towards the authors' work.

2. STATE OF THE ART IN FAST TDIE SOLVER TECHNOLOGY

Modern ground and airborne vehicles come replete with sophisticated electronic communication and navigation systems comprising potentially nonlinear components interconnected by multi-conductor cables (Fig. 1). This section highlights three ingredients that are key to the construction of a direct time domain tool capable of analyzing electromagnetic transients in such systems: (i) a stable TDIE solver for analyzing transient field interactions with conducting and penetrable structures including wire attachments, (ii) accelerators that bring this solvers' CPU and memory requirements in line with those provided by readily available computers, and (iii) interfaces to a variety of subsystem analysis/characterization modules, including circuit and cable analysis tools and macromodelers, to characterize structures too fine to efficiently capture via (i).

2.1 Stable TDIE solvers for conducting and penetrable structures including wire attachments

A typical TDIE solver for analyzing transient electromagnetic scattering from perfect electrically conducting surfaces residing in unbounded 3D lossless environments operates as follows. The extinction theorem states that the electromagnetic field anywhere in space can be evaluated upon specification of the incident field and the total magnetic field, or, equivalently, the current, on the scatterer's surface. By enforcing the tangential component of the total electric field along the surface to vanish, the surface current can be related to the incident field through an electric field TDIE. To solve this TDIE by MOT methods, the surface current is represented in terms of N_s spatial basis functions with unknown amplitudes at N_t time steps. Then, the instantaneous total electric field is expressed as a superposition of the incident and scattered fields. The evaluation of the latter requires the computation of a retarded time boundary integral over the basis functions representing the surface field at a given time step. This procedure leads to a linear system of equations that can be solved for the coefficients of the basis functions. Depending on the choice of the time step size, the basis functions, and the testing procedure, the matrix to be inverted can be diagonal or sparse, yielding explicit or implicit time stepping schemes, respectively. In the past, MOT-based TDIE schemes often were found to be unstable. In recent years, however, the stability of MOT-based TDIE solvers has greatly improved due to the application of averaging/filtering techniques [13], implicit time stepping methods [14], smooth and carefully tailored temporal basis functions [15], and space-time Galerkin schemes [16]. In addition, Calderon identities were leveraged to analytically precondition the MOT system, thereby accelerating convergence. Finally, solvers that target structures far more complicated than simple conducting surfaces, including structures with small geometric details [17], surfaces characterized by impedance boundary conditions [18], surfaces buried in half-space backgrounds [19], dielectric/lossy/dispersive penetrable volumes [6] and surfaces with wire attachments [1], have been developed. The latter were applied to the characterization of complex, platform mounted antennas [11, 20].

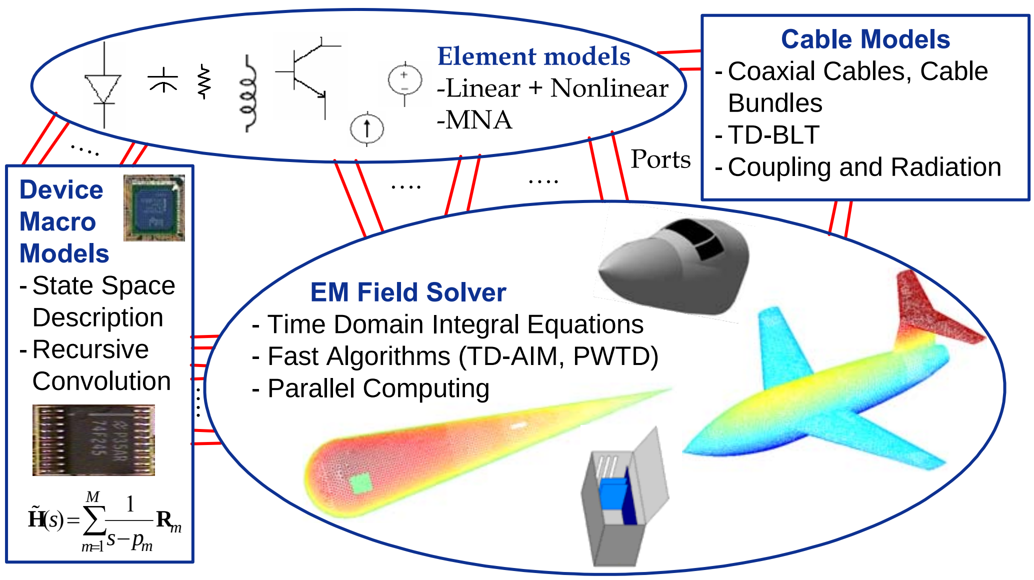

Figure 1. a large scale platform loaded with electronic systems, comprising nonlinearly loaded subsystems interconnected by cables (acronyms are defined in the text below).

2.2 Computational cost and recently developed accelerators

Unfortunately, the computational complexity of the above solvers scales poorly. Indeed, when analyzing electromagnetic transients on 3D surfaces embedded in a free-space background, their complexity scales as $O(N_t N_s^2)$, in all other cases, it scales as $O(N_t^2 N_s^2)$ due to the presence of a Green function wake. To render these solvers applicable to the analysis of large-scale phenomena, they have been augmented with two families of accelerators: the multilevel plane wave time domain (PWTD) algorithm [7] and the time domain adaptive integral method (TD-AIM) [8]. These algorithms permit the fast evaluation of transient electromagnetic fields produced by known, bandlimited sources. Consequently, they reduce the computational complexity and memory requirements of MOT-based TDIE solvers by allowing for the rapid evaluation of time-varying excitation vectors constructed by these solvers during each time step. PWTD methods constitute extensions to the time domain (wave equation) of frequency domain (Helmholtz equation) fast multipole methods [21, 22] and rely on plane wave decompositions and diagonal translation operators to accelerate the classical evaluation of transient wave fields [23]; they reduce the computational complexity of the MOT-based TDIE solver to $O(N_t N_s \log^2 N_s)$ when applied to the analysis of general 3D surfaces. TD-AIM methods exploit the convolutional nature of the underlying Green kernel to achieve speedups by using blocked fast Fourier transforms [4] and reduce the computational complexity to $O(N_t N_s \log^2 N_s)$ when applied to the analysis of quasi-planar structures, and to $O(N_t N_s^{3/2} \log N_s)$ when used to characterize 3D surfaces [8]. Because PWTD schemes exploit the structure of the Green kernel well beyond its convolutional nature, PWTD-accelerated TDIE solvers are more kernel-specific and much more difficult to implement than their TD-AIM counterparts. On the upside, however, they are asymptotically more CPU and memory efficient. Recently, both the PWTD and TD-AIM kernels were parallelized (via the MPI paradigm) and executed on massively parallel architectures.

2.3 Hybridization

Unfortunately, even with PWTD and TD-AIM enhancements in place, the above-described TDIE solvers remain ill-suited for analyzing transient field interactions with structures loaded with ultra-small/subwavelength scale or nonlinear subsystems. To capture their behavior, hybridization of MOT-based TDIE solvers with specialized subsystem tools is called for. For example, to facilitate the efficient analysis of real-world EMI/EMC problems, MOT-based TDIE solvers should be hybridized with a circuit solver as well as with modules that incorporate macromodel descriptions of small subsystems and multiconductor cables. Different applications unavoidably call for the incorporation of different subsystem tools.

2.1 Hybrid field-circuit simulators

Recently, both PWTD- and TD-AIM-accelerated TDIE solvers were coupled to SPICE-like modified nodal analysis-based circuit simulators and applied to the analysis of transients in linear and nonlinear circuits/components supported by large platforms [9, 10]. Hybridization of MOT-based TDIE solvers with circuit solvers results in a coupled nonlinear system of equations, which is solved yia Newton-Raphson iterations to compute the temporal evolution of the fields, currents, and voltages in the entire system. To maintain the parallel scalability of the hybrid solver, the computational work was divided among multiple processors using a simple but effective parallelization paradigm [10]: TDIE and circuit unknowns and associated operations are assigned to separate groups of processors. This strategy allows for the separate development and optimization of TDIE and circuit solvers and results in near-optimal parallel scalability for the hybrid solver.

2.2 Macromodel enhancements

Macromodels (rather than lumped discrete circuit elements) have long been employed by circuit solvers to efficiently capture subsystem responses in system level analysis; the efficiency gains are attained by the use of algorithms for fast convolution (recursively) and for reduced-order model generation. In practice, macromodels can be connected to ports of subsystems modeled either by the circuit- or the TDIE component of the hybrid simulator; hence, they need to be interfaced with both solvers simultaneously. However, the integration of the commonly used admittance parameter macromodels --or any other macromodel defined by a single set of network parameters -- with each simulator requires a separate treatment, because the TDIE solver unknowns are current quantities, while the (modified nodal analysis based) circuit-solver unknowns are voltage quantities. The effective integration of the macromodels with fast hybrid simulators, require the identification of associated computational bottlenecks in the resulting system of equations and the use of fast recursive convolution schemes to overcome these bottlenecks [12].

2.3 Field-Circuit-Cable solvers

The analysis of electromagnetic coupling and signal propagation in large-scale multiconductor transmission-line networks can be carried using 1-D TDIE formalisms based on cable Green functions that account for the guided wave phenomena on dispersive and lossy cables. Such Green functions are often derived from measurements or simplified cable models in frequency-domain; these are then approximated using exponential fitting models to obtain a temporal signature that can be convolved recursively. The FFT-based algorithms as well as implicit time-stepping based stabilization schemes developed for radiation and scattering solvers, have recently been migrated to cable solvers, where they reduce the $O\left(N_t^2\right)$ complexity of these solvers to $O(N_t \log^2 N_t)$, reducing the computational complexity as well as overcoming the need for approximations involved in fitting models [24].

3 APPLICATIONS – FOCUS ON EMI/EMC ANALYSIS

The comprehensive nature of the above-described solver (Fig. 1) is demonstrated through its application to two real-world electromagnetic compatibility and interference problems. In both simulations, the time-step size is $\Delta t = 55$ ps .

The first problem involves the cockpit shown in Fig. 2. The cockpit is illuminated, head on, by a modulated Gaussian plane-wave pulse with parameters specified in Fig. 2. The pulse couples through the cockpit windows, into RG-58 cables that connect three PC boxes loaded with multiple printed circuit boards. The number of unknowns found by the TDIE, cable, and circuit solvers at each time step are $78\,676$, 6, and 16, respectively**.** Various snapshots of the transient currents on the structure are presented in Fig. 3. The figures on the left show surface currents on the cockpit, (the outer surfaces of) the PC boxes, and the cable shields; the figures on the right show the surface currents on (the inner surfaces of) the PC boxes and circuit boards and differential-mode currents inside the coaxial cables: (a) At $t = 200\Delta t$; before the external fields have reached the PC boxes. (b) At $t = 250\Delta t$; when the external fields start to interact with the cable shields. (c) At $t = 350\Delta t$; when coupling from the external fields starts to excite the circuit boards through the horizontal cables. (d) At $t = 500\Delta t$; the external fields continues to excite the inside of the boxes through the horizontal cables.

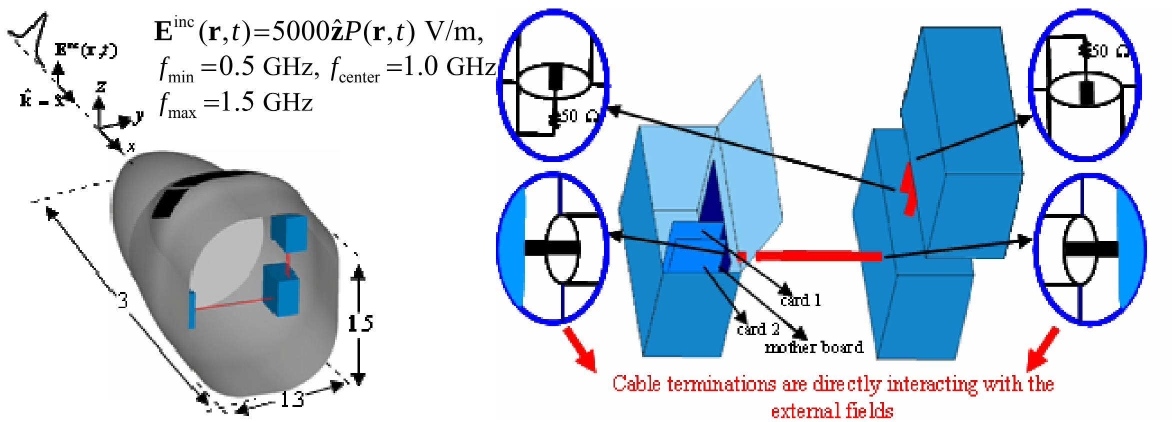

Figure 2. Cockpit illuminated by a head-on pulse.

The second problem involves a set of RG-58 coaxial cables located in a car. The car is illuminated with the pulse described in Fig. 4(a). The number of unknowns found by the TDIE, cable, and circuit solvers at each time step are $128\,934$, 10, and 5, respectively. The induced voltage observed at node 1 is shown in Fig. 4(b). Snapshots of the current induced on the whole structure at two different time-steps are shown in Fig. 4(c).

4 CONCLUSIONS

Fast MOT-based TDIE solvers, appropriately hybridized with tools for analyzing subsystems and components, permit the efficient simulation of electromagnetic transients in complex, real-world systems. Current research into low frequency (loop-tree) stabilizers and high-frequency asymptotic PWTD kernels aims to further broaden these solvers' scope and appeal.

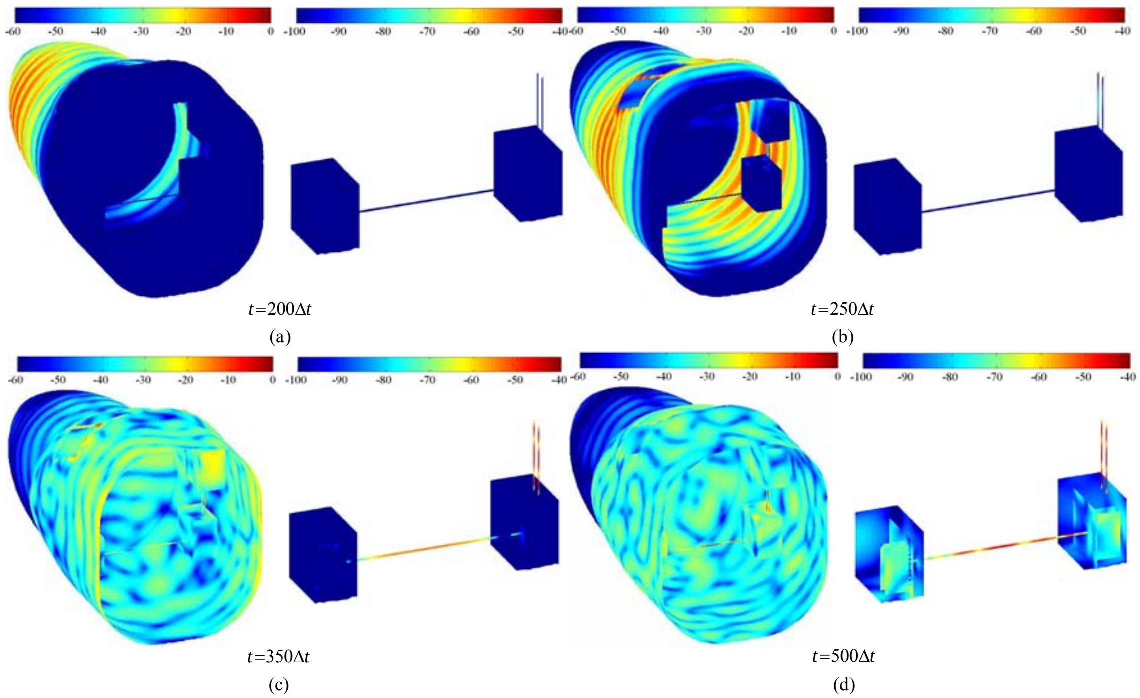

Figure 3. Snapshots of the transient currents on the structure in Fig. 2 (in dB scale).

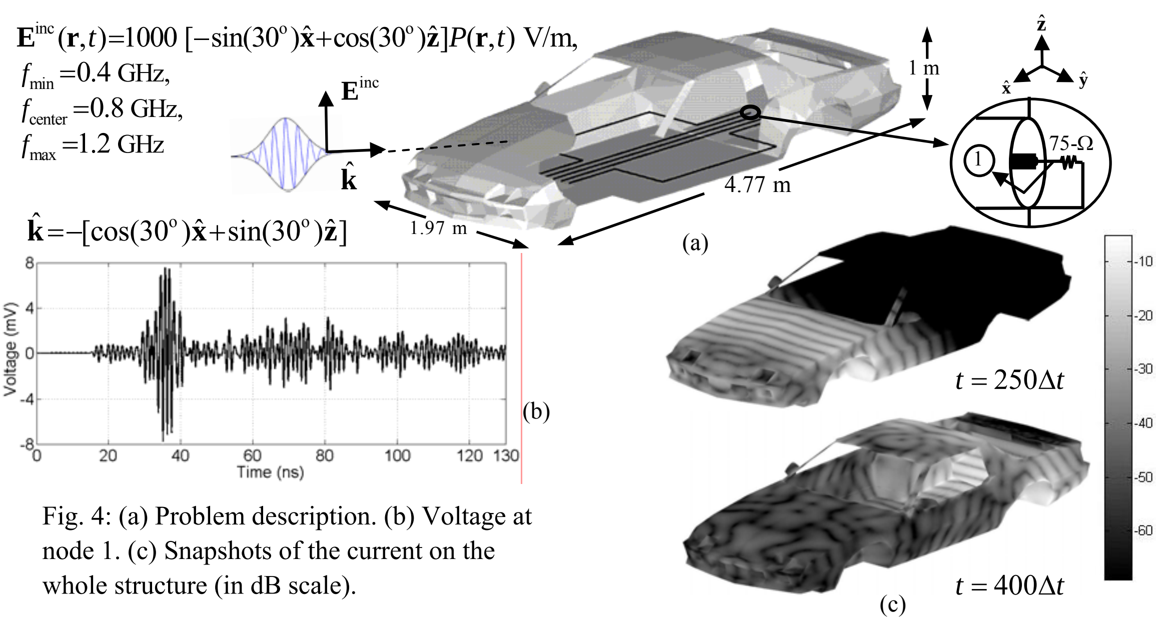

Fig. 4: (a) Problem description. (b) Voltage at node 1. (c) Snapshots of the current on the whole structure (in dB scale).

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