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2-D FINITE ELEMENT CABLE & BOX IEMP ANALYSIS

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ABSTRACT

A 2-D finite element code has been developed for the solution of arbitrary geometry cable SGEMP and box IEMP problems. The quasi-static electric field equations with radiation-induced charge deposition and radiation-induced conductivity are numerically solved on a triangular mesh. Multiple regions of different dielectric materials and multiple conductors are permitted.

INTRODUCTION

The absence of underground nuclear testing makes advanced computational tools for addressing radiation-induced electromagnetic phenomena much more important than in the past. In addition, the cost-driven desire to minimize hardware design iterations, due to problems revealed by radiation testing relatively late in the development process, further increases the need for such analysis capability. This paper describes a code aimed at significantly improving the capability of calculating direct charge injection cable SGEMP response and the IEMP response within electronic boxes.

The purpose of this effort is to develop a computational tool for evaluating direct charge injection effects in lightly shielded cables for systems having reasonably stressing x-ray requirements. Based on cables existing in the present nuclear stockpile and those being considered for future applications, this code must have the capability to treat rather complex geometries consisting of multiple conductors and multiple dielectric regions. The applicable x-ray environments require that radiation-induced conductivity effects be considered in the multiple dielectric regions. Furthermore, the computational approach must be compatible with lumped-element, multi-conductor transmission line analysis in order to evaluate transmission line effects and electrical stresses at termination circuits.

METHODOLOGY

It is assumed that both the incident radiation environment and the transmission line voltages are constant over a section of cable of length (Δz) and that at time (t) the potentials are known for all conductors. It is further assumed that charge density (ρ) within the dielectric regions, due to both direct radiation-induced charge deposition and charge transport by natural and/or radiation-induced conductivity at time (t), is known. Figure 1 depicts the cable geometry being addressed.

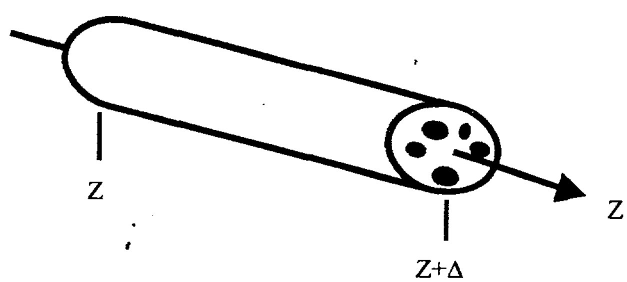

Figure 1. Cable Geometry.

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Letting $\boldsymbol{E} = -\nabla\phi$ represent the transverse electric field, it follows that $\nabla \bullet \varepsilon \boldsymbol{E} = \rho$ where ϕ is the potential and ε is the permittivity within the cable. Define $\boldsymbol{E}_i$ as the electric field in the absence of the internal charge distribution due to a unit potential on the i^{th} conductor with all the remaining conductors grounded. Define $\boldsymbol{E}^*$ as the field due to the internal charge density with all conductors grounded. This implies that $\boldsymbol{E}$ can be written as

$$\boldsymbol{E} = \boldsymbol{E}^* + \Sigma\, \phi_i\, \boldsymbol{E}_i$$

where ϕ_i is the potential on the i^{th} conductor and the sum is over all conductors. It also follows that $\nabla \bullet \varepsilon \boldsymbol{E}^* = \rho$ with the boundary conditions that the potential function associated with $\boldsymbol{E}^*$ must vanish on the surface of all conductors. Given the ϕ_i's and ρ, $\boldsymbol{E}$ can be computed at time t. To advance the solution to time t + Δt, one must be able to advance the ϕ_i's and ρ in time. The charge density is advanced using the charge continuity equation

$$\nabla \bullet \boldsymbol{J}_t + \nabla \bullet \sigma \boldsymbol{E} + \partial\rho/\partial t = 0$$

where $\boldsymbol{J}_t$ is the radiation-driven transport current and $\sigma\boldsymbol{E}$ is the conduction current. The potentials on the conductors are advanced in time by invoking the charge balance relation obtained by integrating the above continuity equation over the volume of each conductor having length Δz. Charge flow in the z-direction due to transmission line currents or conductor terminations must be included.

The numerical solution of the above spatial equations is accomplished using finite element analysis on a triangular mesh. An explicit finite difference procedure is used to advance the solution in time. Mesh generation is accomplished using commercial grid generation software.

CODE DESCRIPTION and RESULTS

The code was written using object-oriented techniques in C++. This allows great extensibility and code reuse. For example, early on it was determined that the accuracy of the electric field for linear elements (field is constant within an element) was inadequate to achieve good charge balance results. Therefore, quadratic elements were introduced (field is linear within an element) in very short order, thereby greatly improving our results. Extension of the code to 3-D has also proved very straightforward with little new code. Essentially the same code now does both 2-D and 3-D analysis.

Figure 2 shows an example cable geometry with two conductors surrounded by a dielectric region and a shield.

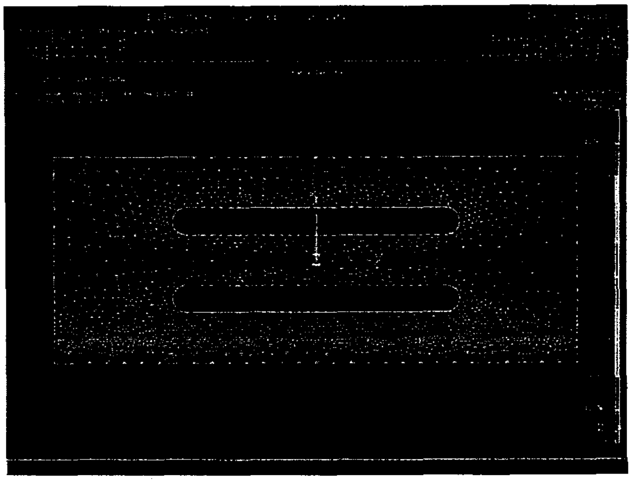

Figure 2. Example cable geometry.

The finite-element mesh is shown along with the elemental charge density distribution 50 time steps into the simulation. The upper section (upper 7/8 vertically, including both conductors) has zero conductivity for all time and zero transport charge deposited. The lower section (lower 1/8 vertically) has a finite conductivity and has transport charge delivered over a triangular pulse having a risetime of 20 time steps and a total length of 40 time steps. The mesh density has been increased near the material discontinuity for greater accuracy. For this simulation, the upper conductor and the shield are grounded while the lower conductor is floating. Therefore, charge will accumulate on the interface between the two materials until all charge is bled to ground through the lower portion of the shield.

The charge existing on the boundary after 50 time steps is shown in Figure 3. In this figure, the charge actually existing on each edge in the boundary is depicted as an "elemental" charge in each of the elements adjacent to the boundary which shares that edge.

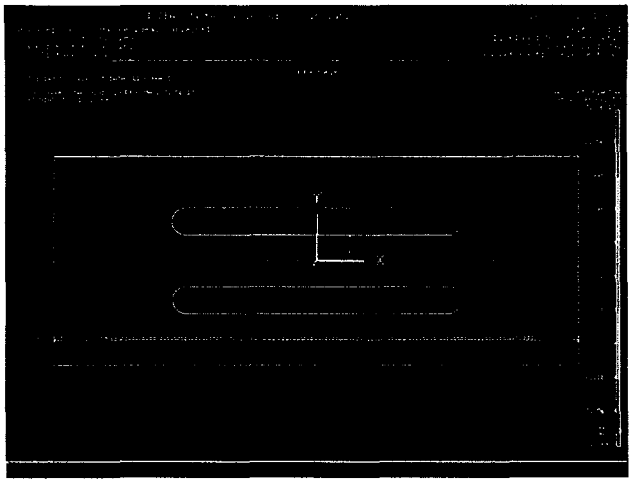

Figure 3. Interface charge at material discontinuity.

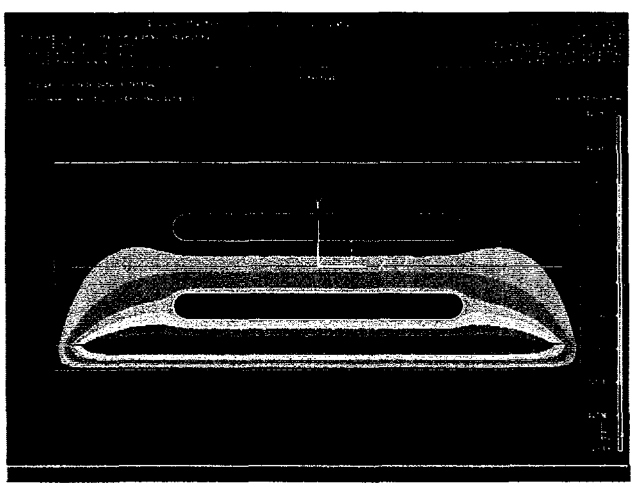

Figure 4. Potential distribution.

Figure 4 shows the potential distribution, also after 50 time steps. Clearly the lower conductor is floating and the others are grounded. Also, the dominant source is now the charge on the interface boundary. Figure 5 shows the replacement current induced in the grounded conductor as a function of time step.

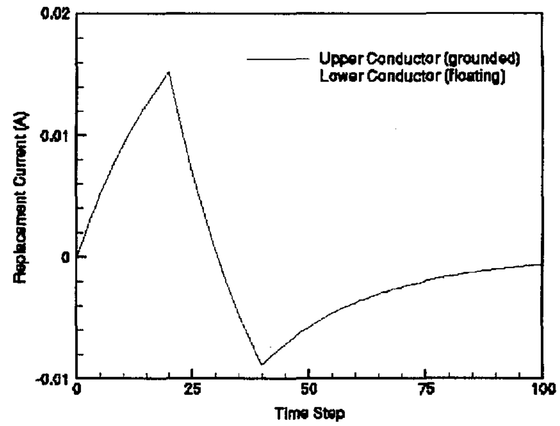

Figure 5. Replacement current through grounded conductor.

DISCUSSION

Although the initial purpose of this work was to develop a code for cable response calculations, the code can also be used to perform 2-D box IEMP calculations with complex geometries and radiation-induced conductivity. The cable shield becomes the metallic-box walls and the conductors become lands. Cable dielectric regions map over into IEMP suppression coatings, potting materials, and printed circuit boards. The numerical techniques utilized in this 2-D code should be directly applicable for a 3-D box IEMP code and, in fact, this development has begun. Perhaps the most significant result of this work is that it provides a methodology for performing cable response calculations without resorting to the approximate equivalent circuit approach used in the past [1]. This previous approach required the analyst to construct a network of parallel capacitors, time-dependent resistors, and time-dependent current sources to approximately represent the radiation-induced phenomena.

As the reader might realize, a 2-D/3-D quasi-static electric field code for cable/box IEMP problems is of limited usefulness unless radiation-transport calculations can be performed for the same geometries. Conceptually, the radiation transport could be performed with a MONTE CARLO code such as ITS [2]. However, obtaining highly accurate charge and energy deposition values with the spatial resolution required to support the quasi-static electric-field analysis would require significant computer resources. A much more desirable approach would be to perform deterministic radiation transport using the same mesh as used for the electrical analysis. Effort is currently underway to develop such a code, first in 2-D, followed by a 3-D version.

REFERENCES

[1] C. E. Wuller, L. C. Nielsen, and D. M. Clement, "Definition of the Linear Region of X-ray-Induced Cable Response," IEEE Transactions on Nuclear Science, Vol. NS-25, No. 4, August, 1978, pp. 1061-1067.

[2] J. A. Halbleib, R. P. Kensek, T. A. Mehlhorn, and G. D. Valdez, "ITS Version 3.0: The Integrated TIGER Series of Coupled Electron/Photon Monte Carlo Transport Codes," SAND91-1634, Sandia National Laboratories Report, 1992.

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