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Efficient Modeling of System Generated Electromagnetic Pulse using Adjoint Methods

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Abstract—System-generated electromagnetic pulse (SGEMP) can compromise system electronics by causing upset or burnout of vulnerable electronics. SGEMP is a complicated process, which is difficult to model accurately, depending sensitively on the energy spectrum and angle of incidence of the driving radiation source, requiring many expensive calculations to fully characterize a threat or test environment. Remarkably, it is possible, with a single adjoint calculation, to determine an SGEMP response for all source energies and angles of incidence.

Index Terms—SGEMP, adjoint methods, radiation transport, uncertainty quantification

I. INTRODUCTION

System-generated electromagnetic pulse (SGEMP) can compromise system electronics by causing upset or burnout of vulnerable systems. SGEMP is a complicated process that is difficult to compute accurately [1], depending strongly on the energy spectrum and angle of incidence of the driving radiation source, often requiring many expensive calculations to fully characterize a test or threat environment. Remarkably, it is possible using adjoint radiation transport to fully characterize a cable SGEMP drive with a single adjoint calculation. A single adjoint calculation can provide, for example, the drive charge for all energies and angles of incidence of the driving radiation source [2]. The application of adjoint methods to cable SGEMP analysis will be described, as well as the utility of adjoint methods for design, test and uncertainty quantification (UQ).

Modeling SGEMP is a two-step process. In a forward calculation, a radiation transport code is used to determine the electron distribution and electron surface emission from electron production due to photoelectric-effect and Compton-scattering interactions of the driving photon source environment. The second step in the analysis is to use an EM/circuit code to compute the drive currents and voltages from the electron distributions and emissions provided by the radiation transport code. In this work, SCEPTRE [3] is used for the radiation transport modeling, and EMPHASIS [4] is used for the EM/circuit modeling.

In an adjoint analysis, the calculation is essentially performed backwards, from the SGEMP response term to the driving radiation source term. Since EMPHASIS does not have adjoint capability, a Poisson solver that has been incorporated into the SCEPTRE code to compute the relevant adjoint source term, which is used in an adjoint mode SCEPTRE radiation transport calculation. The result of an adjoint calculation, with an appropriate adjoint source term, is the adjoint photon fluence, which can be interpreted as the impulse contribution to the SGEMP drive charge as a function of the photon source energy and angle of incidence.

II. FORWARD SGEMP ANALYSIS

SGEMP direct drive current is generated by two mechanisms: 1) electrons that are directly knocked off of the load conductor, and 2) electrons that are induced on the load conductor by charge deposited in the surrounding dielectric materials. The knock-on charge component is

$$q_{ko} = \oint \mathbf{J}_\beta(\boldsymbol{r}) \cdot d\boldsymbol{s}, \quad (1)$$

where $\mathbf{J}_\beta(\boldsymbol{r})$ is the electron current distribution vector at spatial location $\boldsymbol{r}$, and the surface integral is performed over the dielectric-conductor interface. $d\boldsymbol{s}$ is an element of surface area, directed outwardly from the conductor to the dielectric. The induced charge is given by the Shockley-Ramo Theorem [5]

$$q_i = -\int V(\boldsymbol{r})\,\rho(\boldsymbol{r})d\boldsymbol{r}, \qquad (2)$$

where $V(\boldsymbol{r})$ is a potential function, which is the solution of the Laplace equation, with boundary conditions of unity on the load conductor of interest and zero on the other conductors and the ground. $\rho(\boldsymbol{r})$ is the spatial distribution of the charge deposition in the dielectric. The spatial integral is performed over the dielectric regions adjacent to the load conductor.

After some manipulation, the net total charge is

$$q_{net} = q_{ko} - q_i = \int \nabla V(\boldsymbol{r}) \cdot \mathbf{J}_{\beta}(\boldsymbol{r})d\boldsymbol{r}. \qquad (3)$$

As an illustration of a forward-mode SGEMP analysis, consider the simple 2-conductor, solid-dielectric, solid-shielded cable shown in Fig. 1.

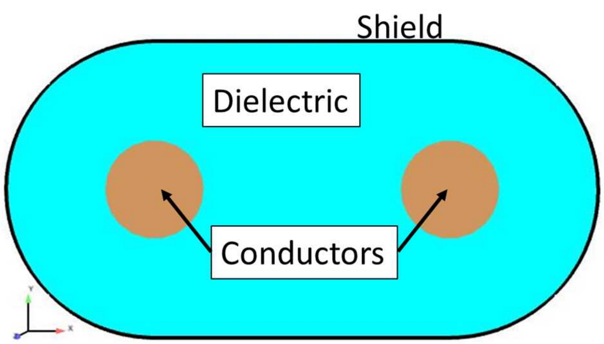

Fig. 1. Cross sectional sketch of two-conductor solid shield cable for demonstration of the forward/adjoint modeling capability.

For example, for a source of 200-keV photons incident from the upper left, the electron distribution computed by SCEPTRE is shown in Fig. 2. The figure shows significant electron emission from the ground shield and from both conductors, and also reveals photon attenuation through both of the conductors.

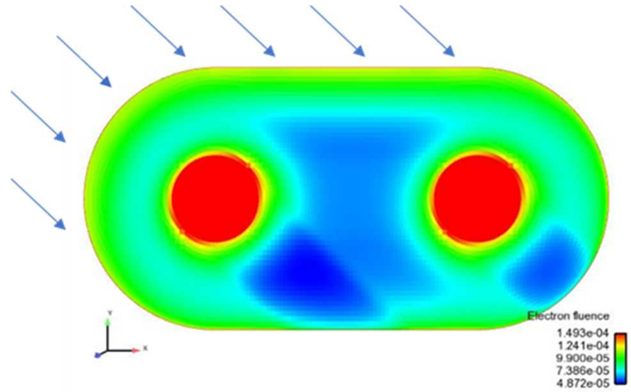

Fig. 2. Electron distribution in two-conductor shielded cable for 200-keV planar photon source incident from the upper left.

Fig. 3 shows the electric field distribution for a load connected to the right conductor, where the electric field is given by $\boldsymbol{\mathcal{E}}(\boldsymbol{r}) = -\nabla V$.

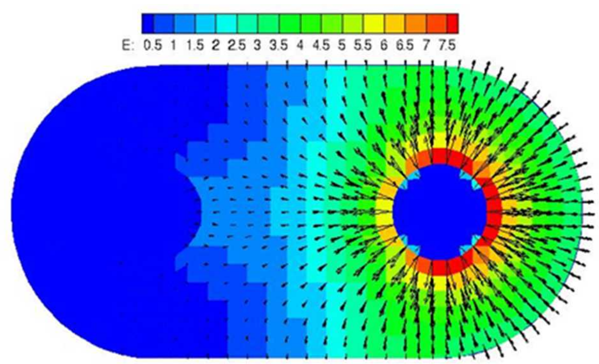

Fig. 3. Electric field vector, $\boldsymbol{\mathcal{E}}(\boldsymbol{r})$, distribution for two-conductor shielded cable for load connected to conductor on the right.

The SGEMP drive is computed from Eq. (3), as the dot product between the electric field vector and the electron current vector, integrated over the dielectric regions. The electron current distribution is computed with the SCEPTRE code, and the EM modeling to compute the total drive charge may be computed using either the EMPHASIS code or the Poisson solver in the SCEPTRE code. The result of using either method is identical, as shown in Table I. The result for an adjoint analysis (described in the next section) is also identical.

TABLE I
Comparison of SGEMP computed from Eq. (3) using the SCEPTRE Poisson solver and EMPHASIS/CABANA

Method	Drive charge $\left(\frac{electrons/cm}{photon/cm^2}\right)$
EMPHASIS/CABANA	$1.67\text{x}10^{-5}$
SCEPTRE/Poisson (forward)	$1.67\text{x}10^{-5}$
SCEPTRE/Poisson (adjoint)	$1.67\text{x}10^{-5}$

III. ADJOINT SGEMP ANALYSIS

An adjoint calculation is essentially performed backwards from detector to source, rather than from source to detector [6]. An adjoint calculation provides extremely useful information, including the sensitivity of the response (in this case, the SGEMP) to the source energy spectrum and angle of incidence.

The first step in performing an adjoint calculation is to compute an adjoint source term. Starting from Eq. (3), after some manipulation, the SGEMP direct drive response can be computed from the angular electron fluence as

$$q_{net} = -\iint \boldsymbol{\Omega}\cdot\boldsymbol{\mathcal{E}}(\boldsymbol{r})\psi_\beta(\boldsymbol{r},\boldsymbol{\Omega})d\boldsymbol{r}d\boldsymbol{\Omega}, \tag{4}$$

where $\psi_\beta(\boldsymbol{r},\boldsymbol{\Omega})$ is the electron angular fluence and $\boldsymbol{\Omega}$ is the electron direction of motion. The electron current is related to the electron fluence by

$$\mathbf{J}_\beta(\boldsymbol{r}) = \int \boldsymbol{\Omega}\psi_\beta(\boldsymbol{r},\boldsymbol{\Omega})d\boldsymbol{\Omega}, \tag{5}$$

The forward and adjoint solutions are related to each other by [6]

$$\iint Q_\beta^\dagger(\boldsymbol{r},\boldsymbol{\Omega})\psi_\beta(\boldsymbol{r},\boldsymbol{\Omega})d\boldsymbol{r}d\boldsymbol{\Omega} = \int\oint \psi_{ph}^b(\boldsymbol{r},\boldsymbol{\Omega})\psi_{ph}^{\dagger b}(\boldsymbol{r},\boldsymbol{\Omega})d\boldsymbol{s}d\boldsymbol{\Omega}, \tag{6}$$

where $Q_\beta^\dagger$ is the adjoint electron source, ψ_{ph}^b is the photon fluence on the external boundary and $\psi_{ph}^{\dagger b}$ is the adjoint photon fluence on the external boundary. $d\boldsymbol{s}$ is an element of surface area on the external boundary of the shield, directed outwardly. By comparing Eq. (6) with Eq. (4), for an adjoint source in the dielectric of

$$Q_\beta^\dagger(\boldsymbol{r},\boldsymbol{\Omega}) = -\boldsymbol{\Omega}\cdot\boldsymbol{\mathcal{E}}(\boldsymbol{r}), \tag{7}$$

the SGEMP drive may be computed from

$$q_{net} = \int\oint \psi_{ph}^b(\boldsymbol{r},\boldsymbol{\Omega})\psi_{ph}^{\dagger b}(\boldsymbol{r},\boldsymbol{\Omega})d\boldsymbol{s}d\boldsymbol{\Omega}. \tag{8}$$

By including the energy dependence of the photon source and the adjoint fluence, the SGEMP drive is

$$q_{net} = \int\int\oint \psi_{ph}^b(\boldsymbol{r},\boldsymbol{\Omega},E)\psi_{ph}^{\dagger b}(\boldsymbol{r},\boldsymbol{\Omega},E)d\boldsymbol{s}d\boldsymbol{\Omega}dE, \tag{9}$$

where E is the photon energy. The power of the adjoint method can be seen in Eq. (9), which enables the calculation of the total drive charge for any photon source term by performing an integral over energy and angle, and a surface integral over space, which is much easier than performing a complete analysis for each photon source term.

The results of an adjoint analysis for the two-conductor cable are shown in Fig. 4, which plots the adjoint photon boundary fluence, with only four specific angles-of-incidence included, for clarity. For mono-energetic photon sources, the total charge can be determined directly from Fig. 4, for the desired photon source angle-of-incidence. For a specific photon source spectrum, the total charge can be determined by folding the energy dependence of the photon source with the desired adjoint fluence curve.

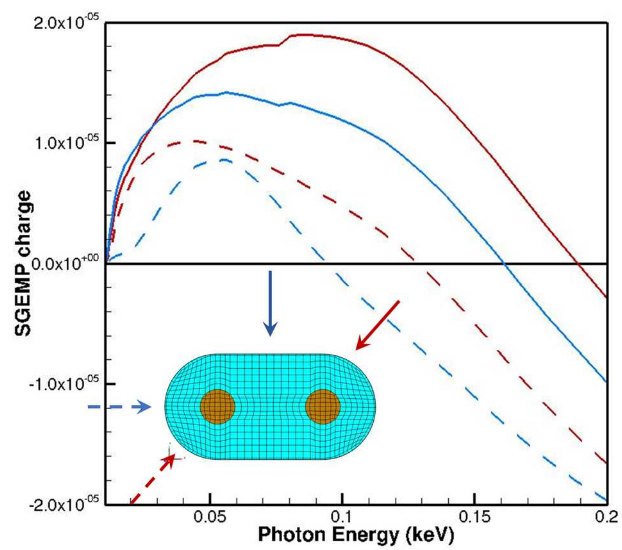

Fig. 4. Adjoint SGEMP results showing total charge as a function of source energy for selected angles on incidence.

A further utility of the adjoint method is uncertainty quantification in the source environment on the SGEMP response, which is still under development. For a given perturbation in the photon source term, $\delta\psi_{ph}^b(\boldsymbol{r},\boldsymbol{\Omega},E)$, the corresponding perturbation in the total charge is given by [7]

$$\delta q_{net} = \int\int\oint \delta\psi_{ph}^b(\boldsymbol{r},\boldsymbol{\Omega},E)\psi_{ph}^{\dagger b}(\boldsymbol{r},\boldsymbol{\Omega},E)d\boldsymbol{s}d\boldsymbol{\Omega}dE. \tag{10}$$

For a constraint on the total energy in the source term, the perturbation in the photon source term is not arbitrary, but is constrained by,

$$\int E\left(\psi_{ph,0}^{b}(E)+\delta\psi_{ph}^{b}(E)\right)\mathrm{d}E = \int E\psi_{ph,0}^{b}(E)\mathrm{d}E, \tag{11a}$$

where $\psi_{ph,0}^{b}(E)$ is the baseline source energy spectrum. Eq. (11a) can be simplified to

$$\int E\delta\psi_{ph}^{b}(E)\mathrm{d}E = 0. \tag{11b}$$

IV. Conclusions

The application of the adjoint method to computing cable SGEMP drive charge has been presented. The application has been limited to steady-state analysis, but time dependence could be included if desired. An adjoint time-dependence analysis proceeds backwards in time, for the final time to the start time. A simple two-conductor shielded cable has been used for illustrative purposes, but the methods presented here could be readily applied to constructed or proposed cable designs in either test or threat environments.

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