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3-D Electromagnetic Modeling of Wakefields in Accelerator Components^{*}

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Abstract. We discuss the use of 3-D finite-difference time-domain (FDTD) electromagnetic codes for the modeling of accelerator components. Computational modeling of cylindrically symmetric structures such as induction accelerator cells has been extremely successful in predicting the wake potential and wake impedances of these structures, but fully 3-D modeling of complex structures has been limited due to the substantial computer resources required for a fully 3-D model. New massively parallel 3-D time domain electromagnetic codes now under development using conforming unstructured meshes allow a substantial increase in the geometric fidelity of the structures being modeled. Development of these new codes will be discussed in the context of their applicability to accelerator problems. A variety of 3-D structures are tested with an existing cubical cell FDTD code and the wake impedances are compared with simple analytic models for the structures. These results will provide a set of benchmarks for testing the new time domain codes. Structures under consideration include a stripline beam position monitor as well as circular and elliptical apertures in circular waveguides. Excellent agreement for the monopole and dipole impedances with the models are found for these structures below the cutoff frequency of the beam line.

INTRODUCTION

As a charge bunch passes a perturbation in an accelerator structure a wakefield is generated which can interact with the charged particle beam. This process can lead to degradation of the beam, or worse, can lead to beam breakup instabilities. A substantial amount of work in the analysis of cylindrically symmetric accelerator structures has been done using the 2-D finite-difference time-domain (FDTD) code, AMOS (azimuthal mode simulator) (1), for the calculation of the wake potential and wake impedances of these structures. More complicated

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accelerator structures do not have the cylindrical symmetry required by AMOS for solution of the wake properties of the structure. We use a 3-D FDTD code, TSAR (temporal scattering and response) to model more general structures that do not necessarily possess cylindrical symmetry.

TSAR uses a 3-D grid composed of cubical cells for the FDTD analysis, with each cell being assigned a given material property. The cell size is typically chosen to resolve the shortest wavelength expected in the problem and is chosen small enough to accurately represent the smallest dimension in the model. In addition, to satisfy stability requirements for the FDTD field solver, the Courant condition for the time step must be satisfied. This condition is defined in Equation (1)

$$dt < \frac{1}{2c} dx \quad (1)$$

where dx is the length of a cell edge. It is also important to resolve the lowest frequency that the electron beam may excite which determines the total number of time steps to be run for a specific problem.

The concept of the wake potential and wake impedance is traditionally used as a measure of the interaction of the beam with the structure it is traversing and has been discussed elsewhere in the literature (2). TSAR is used to perform 3-D modeling of the wakefields associated with a stripline beam position monitor and beam line aperture to determine the longitudinal monopole ($m = 0$) and transverse dipole ($m = 1$) impedances.

Beam Position Monitor

The stripline beam position monitor is discussed in some detail by Ng (3). The beam position monitor consists of 2 pairs of strip transmission lines shown schematically in Figure (1). The dimensions of the structure are shown in the figure. The 25Ω terminating resistors were chosen based on a frequency domain calculation of the TEM impedance of a single stripline in the enclosure that resulted in a 25Ω characteristic impedance. Since the four striplines are not strongly coupled due to the proximity of the striplines to the enclosure and the large angular sector between them, 25Ω is a good estimate of the impedance for each stripline. For modeling purposes, the terminating resistors represent external coaxial transmission line feeds to the strip lines. Even to represent the gross geometric characteristics of the structure using cubical cells requires a cell size of 0.5 mm making the computational size of this problem 8×10^6 cells and requires a time step of .83 ps as dictated by the Courant condition. To accurately represent

the details of the coaxial feeds would have required a much smaller cell size to have adequate geometric fidelity in the feed region and therefore it was decided to use simple wire resistors to model this region to minimize the computer memory requirements for the model. The length of the striplines was 10 cm which indicates a quarter-wavelength resonance of 750 MHz allowing us to sufficiently resolve the low frequency behavior using 16000 time steps. Approximately 25 cm of beam transport line was used on each side of the beam position monitor to

FIGURE 1. Model of beam position monitor for determining wake impedances

allow evanescent waves to decay and minimize the effects of the MUR radiation boundary conditions applied to the ends of the problem space. The structure is excited with a current distribution of the form

$$J_z = I_0 \delta(r - r_0) \delta(\phi - \phi_0) \delta(ct - z) \quad (2)$$

where I_0 represents the strength of the current source, (r_0, ϕ_0) represent the transverse location of the relativistic electron beam, and $\delta(ct - z)$ represents the motion of a relativistic point charge. Analytic expressions for the longitudinal monopole ($m = 0$) and transverse dipole ($m = 1$) impedances were found for a matched transmission line model of the beam position monitor by Ng (3) as

$$Z_1 = Z_s \left(\frac{\phi_s}{2\pi} \right)^2 \left[\sin^2 \left(\frac{\omega L}{c} \right) + j \sin \left(\frac{\omega L}{c} \right) \cos \left(\frac{\omega L}{c} \right) \right] \quad (3)$$

$$Z_1 = \frac{8cZ_s}{\pi^2 R_s^2} \left(\frac{1}{\omega} \right) \sin^2 \left(\frac{\phi_s}{2} \right) \left[\sin^2 \left(\frac{\omega L}{c} \right) + j \sin \left(\frac{\omega L}{c} \right) \cos \left(\frac{\omega L}{c} \right) \right] \quad (4)$$

Figures (2) and (3) show comparisons of the analytic models with results obtained numerically through the TSAR modeling code for the longitudinal and transverse impedances respectively. As is seen there is excellent low frequency agreement. The deviation at higher frequencies may possibly be attributed to the high frequency impedance of the wire resistors.

FIGURE 2. Real and Imaginary Longitudinal Impedance of the Beam Position Monitor

FIGURE 3. Real and Imaginary Transverse Impedance of the Beam Position Monitor

Circular Aperture in Circular Beam Line

The impedance of coupling apertures in beam transport lines has been treated in the literature by Gluckstern (4) and Kurennoy (5). In this section we consider a 3 cm diameter cylindrical beam line with either an 8 mm or a 3 cm circular

waveguide connected at 90° to the beam line as shown in Figure (4). The 3 ports of the problem space are terminated with MUR radiation boundary conditions. A cell size of 0.5 mm is used to model both aperture problems. The length of the beamline is about 30 cm and the coupling waveguide is 3 cm long resulting in a mesh of about 1.2×10^7 cells.

FIGURE 4. Geometry of the Beam Line Aperture Problem

An analytic expression for the low frequency transverse dipole impedance is given by Equation (5).

$$Z_{\perp} = j \frac{2a^3 Z_0}{3\pi^2 R_0^4} f(w) \quad (5)$$

In Equation (5) Z_0 is the impedance of free space and the factor of $f(w)$ is a correction factor based on the length of the coupling guide and has a value of 0.562 for $w/a > 2$ as defined in Gluckstern (4). In our model, $w = 3$ cm. For the 8 mm coupling guide Equation (5) gives an inductive transverse impedance of 18.1Ω and the TSAR model predicts an inductive transverse impedance of 18.3Ω for frequencies up to 6 GHz. Figure (5) shows the TSAR results for the 3 cm large aperture case for the transverse impedance along with the low frequency asymptote for the reactive component of the impedance. The real part arises from the fact that the secondary coupling waveguide is only 3 cm long in the model and does not let low frequency fields evanesce sufficiently before reaching the MUR boundary condition on the coupling guide. This accounts for the resonance at the TE_{11} cutoff at 5.9 GHz.

FIGURE 5. Transverse Impedance of the 3 cm Diameter Coupling Waveguide

SUMMARY AND CODE IMPROVEMENTS

While excellent results were obtained using TSAR for our geometries, 3-D cubical cell FDTD codes are extremely limited in the problems that can be modeled. New 3-D codes are being developed that will extend the complexity of structures that can be modeled. These new codes include such features as conforming grids, hybrid structured/unstructured grids, massively parallel capability, and new radiation boundary conditions. Conforming grids eliminate stair-casing errors associated with cubical cell codes. However, conforming unstructured nonorthogonal grids require typically 30 times the memory overhead compared to structured orthogonal grids. Hybrid grids can overcome this limitation by only using conforming grids near appropriate surfaces and structured grids elsewhere. Advanced radiation boundary conditions can also reduce the computational effort by allowing a closer truncation of the problem space.

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