EE692 Applied EM- FDTD Method
Chapter 1 Electrodynamics Entering the 21st Century Notes

What is the FDTD method?

- It is a means of taking spatial and time differential equations (e.g., Ampere's and Faraday's Laws) and expressing them in a linear discretized form allowing for the direct solution of field components.
- The discretization is accomplished using second-order accurate central-difference approximations to the spatial and time derivatives.
- The spatial discretizations are usually on the order of λ /10 to λ/20 at the highest frequency of interest.
- The time steps are chosen to ensure stability.
- The field quantities are interleaved in both space and time in a fashion that allows for successive updating (update equations) with an algorithm referred to as 'time-steping', 'leapfrog', 'recursive', or 'time-marching'. That is, to calculate a field quantity at some time uses the value of that field quantity from the prior time-step as well as spatially adjacent related field quantities from a half time-step back.

FDTD advantages

- No matrices to invert, unlike MoM and finite-elements techniques. The mathematical requirements of matrix inversion limit the number of variables to about to around 10^6.
- FDTD gives good results and is fairly stable (barring programming errors). Techniques which require matrix inversion can be troublesome (singularities/ divide by zero errors).
- Direct time-domain solution. Nearly any bandlimited, time-function signal (e.g., Gaussian pulse, sinusoidal monocycle, half-wave rectified sinusoid, etc.) can be applied. Good for impulses.

FDTD advantages cont.

- Can handle non-linear behavior directly (consequence of being a time-domain solution technique).
- Tremendous flexibility in modeling shapes (e.g., no problems with irregular or asymmetric geometries). Changes can be made on a cell-by-cell basis.
- Don’t need to re-work underlying equations each time the problem geometry or materials change. E.g., don’t need new Green’s function (ala MoM) each time.
- Tremendous flexibility in modeling different materials (e.g., ε, μ, and σ). These can be specified on a cell-by-cell basis.
- Algorithm is highly parallelizable, i.e., computers with multiple processors highly advantageous. FDTD can take advantage of advances in computers.

FDTD Concerns/Disadvantages

- Computationally intensive in terms of both memory and processing. For example, 3 dimensional problems can have 6 field components (e.g., E_x, E_y, E_z, H_x, H_y, and H_z) and 3 material coefficients (e.g., ε, μ, and σ) per unit cell in the mesh with each cell having dimensions on the order of 0.1λ. Therefore, to model a cubic volume of space 30λ per side could require $9 \times 300^3 \times 8$ bytes/quantity = 2 GB at single precision (4 GB at double precision)!
- Frequency-domain results are usually calculated using the Fourier transform. Alternatively, a single frequency sinusoid can be used as the excitation and the algorithm run long enough for steady-state results.
- Small features such as thin sheets/wires or narrow slots require excessively small unit cells or special care (e.g., sub-cell models)
- Open geometries necessitate special treatment, e.g., absorbing boundary conditions (ABCs), for simulation, or the model space must be extended so that reflections from where the grid is truncated do not reach the space of interest
- Special algorithms are required to get far-field results, i.e., near-field results must be translated into the far-field (usually involves saving field quantities on some closed surface over some time-period).

FDTD Applications

- Scattering (e.g., radar cross section) modeling
- EMI/EMC
- Modeling layered, inhomogeneous, and/or anisotropic materials (e.g., soils, stealth materials)
- Time-domain or short-pulse radars (e.g., ground penetrating radars)
- Antenna design
- Biological EM interactions (e.g., cell phones and human body)
- Digital & microwave circuits and devices
- Optical devices
- Many others

FDTD History (see Table 1.1)

- 1966 Yee publishes first paper, not much interest as computer resources limited
- late 1970's Taflove/Brodwin (EM & biological interactions) and Holland/Kunz (electromagnetic pulse or EMP) apply FDTD
- 1980's FDTD gains acceptance- simulation of scattering problems (e.g., RCS), lumped circuit models, waveguides, subcell models for thin wires & slots, microstrip, analytic absorbing boundary conditions (ABCs), human body, etc.
- 1990's takes-off as computer resources become more common place-simulation of antennas, dispersive materials, perfectly matched layer ABCs, etc.

FDTD Algorithm Classes/Types

Differentiatated by how the spatial discretization/gridding is done.

1) Structured/nearly-structured
    - uniform unit cells wherever possible
    - typically use staircasing to fit cells to objects/structures
    - can use limited number of conformal cells at surface of objects/structures
2) Surface-fitted
    - spatial lattice is globally distorted to fit objects/structures (cells same general shape)
    - need mesh-generation software (readily available from earlier finite-elements work)
    - causes additional computational burden (check that fields meet boundary conditions and keep track of how cells were distorted)
    - added risk of numerical attenuation can limit problem size
3) Unstructured
    - spatial lattice consists of cells of varying shapes & sizes fitted to objects/structures
    - can handle very complicated objects/structures
    - need mesh-generation software (available from earlier finite-elements work)
    - causes additional computational burden (check that fields meet boundary conditions and keep track of how cells were distorted)
    - potential for numerical inaccuracy and instability
    - more difficult to efficiently utilize parallel processing

FDTD Algorithm Predictive Dynamic Range

- Defined by power density (W/m^2) of applied/incident/principle signal/wave (P_0) to the minimum scattered/secondary signal/wave (P_S) that can be observed which is limited by numerical artifacts
- limited by reflections from external boundary of computational volume, grid discontinuities, etc.
- Similar to SNR in electronic circuits.
- Usually *Predictive Dynamic Range* is expressed in decibels as $10\log_{10}(P_0 / P_S)$
- With analytic absorbing boundary conditions (ABCs), the predictive dynamic range was around 40 to 50 dB
- With perfectly matched layer (PML) ABCs, the predictive dynamic range was improved to around 70 to 80 dB

FDTD Algorithm Scaling

1) Number of cells in grid N (usually six field components per cell for 3D)

2) Number of time steps

3) Cumulative errors