# Time-Domain Response of 3-D Waveguide and Scattering Structures Calculated by Higher Order Frequency-Domain FEM Technique and DFT

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The finite element method (FEM) is one of the most powerful and versatile general numerical tools for full-wave computations based on discretizing partial differential equations in electromagnetics. It has been especially effectively used in simulations of three-dimensional (3-D) closed- and open-region electromagnetic structures in the frequency domain. However, time-domain analysis and characterization of such structures and evaluation of associated transient electromagnetic phenomena are also of great practical importance for a number of well-established and emerging areas of applied electromagnetics, including wideband communication, electromagnetic compatibility, packaging, signal integrity, material characterization, and other applications. For this purpose, time-domain FEM techniques have recently been developed that allow electromagnetic phenomena to be modeled directly in the time domain. When compared to frequency-domain FEM solutions, time-domain FEM formulations enable effective modeling of time-varying and nonlinear problems and fast broadband simulations, at the expense of the additional discretization, in the time domain, and the associated numerical complexities, and programming and implementation difficulties.

An alternative approach, an indirect time-domain analysis, that is, finding the transient response of an electromagnetic structure based on the frequency-domain FEM analysis coupled to the discrete Fourier transform (DFT) and its inverse (IDFT), has not been widely exploited. This is most likely because such an analysis would require FEM solutions with many unknowns at many discrete frequency points, which may be computationally prohibitively costly. However, with a highly efficient and appropriately designed frequency-domain FEM technique, it is possible to obtain very fast and accurate time-domain solutions performing computations in the frequency domain along with the DFT/IDFT (E. M. Klopf, S. B. Manic, M. M. Ilic, and B. M. Notaros, "Efficient Time-Domain Analysis of Waveguide Discontinuities Using Higher Order FEM in Frequency Domain," Progress In Electromagnetics Research, Vol. 120, 2011, pp. 215-234). Our solutions are based on a higher order large-domain 3-D FEM implementing Lagrange-type generalized curved parametric hexahedral finite elements, filled with anisotropic inhomogeneous materials with continuous spatial variations of complex relative permittivity and permeability tensors, and curl-conforming hierarchical polynomial vector basis functions for the approximation of the electric field intensity vector within the elements, in conjunction with standard DFT and IDFT algorithms. In this paper, we extend the time-from-frequency-domain FEM approach to additional examples of closed-region microwave waveguide structures, with a simple single-mode boundary condition introduced across the waveguide ports and a large buffer finite element at each port to ensure relaxation of higher modes. We also analyze open-region scattering structures, with a truncation of the FEM domain by a hybridization with a higher order method of moments. Numerical examples demonstrate excellent numerical properties of the time-from-frequency-domain FEM solver based on a small total number of unknowns in higher order solutions, modeling flexibility using large curved inhomogeneous finite elements, and fast FEM solutions at multiple frequencies needed for the IDFT.