Higher Order Electromagnetic Modeling for Wireless Technology Applications

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This paper presents our development of novel higher order electromagnetic (EM) modeling techniques for wireless technology applications based on the method of moments (MoM), finite element method (FEM), and physical optics (PO). Modern wireless systems involve electrically large EM structures (antennas, circuits, and components) that are very complex in both geometry and material composition. There is a clear need for advanced analysis and design tools for predicting the performance and optimizing the parameters of such structures prior to costly prototype development. In addition, EM tools are needed for indoor and outdoor propagation modeling, for assessing EM interactions with human bodies, etc. These tools have to be very accurate and reliable. Wireless designers also demand that the simulation techniques be fast and run on relatively small computing platforms, such as standard desktop PCs. Generally, MoM is very efficient at modeling of open-region (e.g., antenna/scattering) problems, while FEM is an excellent choice for modeling of closed-region (e.g., waveguide/cavity) problems. Finally, PO is extremely cost effective for structures that include electrically very large surfaces with slowly varying currents, especially when hybridized with MoM.

Our MoM technique is based on using generalized curvilinear quadrilaterals of arbitrary geometrical orders for the approximation of metallic and dielectric surfaces in conjunction with hierarchical divergence-conforming polynomial vector basis functions of arbitrary orders for the approximation of surface electric and magnetic currents, and we refer to it as a double-higher-order method [1]. Our FEM technique employs hierarchical curl-conforming vector basis functions of higher polynomial orders defined in generalized curved hexahedra of higher geometrical orders [2]. The two techniques enable using large curved MoM quadrilaterals and FEM hexahedra that are on the order of two wavelengths in each dimension. Our hybrid MoM-PO technique uses hierarchical basis functions in the MoM region and higher order interpolatory polynomial functions in the PO region. This mixed approach results in an extremely fast and accurate EM tool.

As the first example of higher order MoM modeling, consider a spherical metallic scatterer. Five different models are implemented, constructed from (A) 216, (B) 384, and (C) 600 first-order geometrical quadrilateral elements with the second-order current approximation and from (D) 6 and (E) 24 fourth-order quadrilaterals in conjunction with the eighth- and sixth-order current approximation, respectively [1]. The RCS results in Fig.1 show that both components of the double-higher-order modeling, i.e., higher-order geometrical modeling and higher-order current modeling, are essential for accurate and efficient MoM analysis of structures with pronounced curvature.

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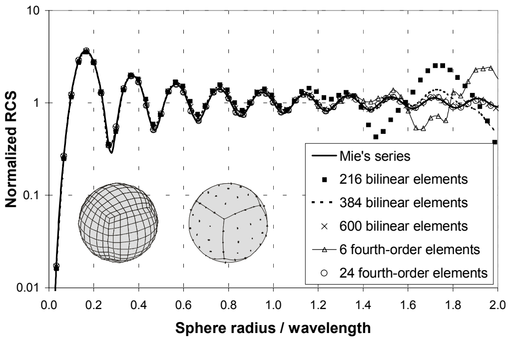
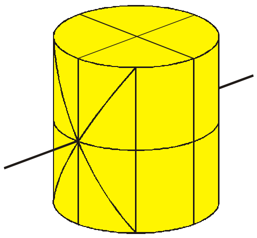


Fig.1. Normalized RCS of a metallic sphere, for five higher-order MoM models.



<u>Low-order MoM</u>
[Hodges, Rahmat-Samii]
$Z_1 = (145.5+j165.0)\ \Omega$
$Z_2 = (30.0-j20.2)\ \Omega$

<u>Higher-order MoM</u>
$Z_1 = (155.1+j167.4)\ \Omega$
$Z_2 = (30.0–j20.9)\ \Omega$

Z_1 – configuration (1)
Z_2 – configuration (2)

Fig.2. A metallic cylinder with two attached wires and the antenna impedance results.

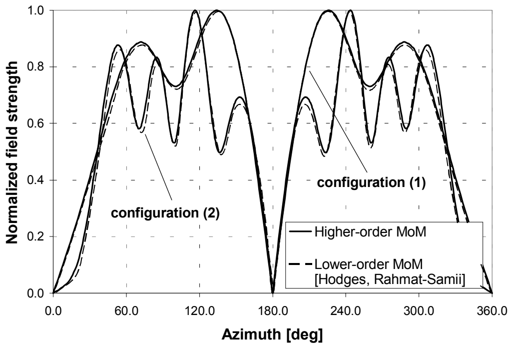


Fig.3. Far field of the antenna system in Fig.2 for two configurations described in the text.

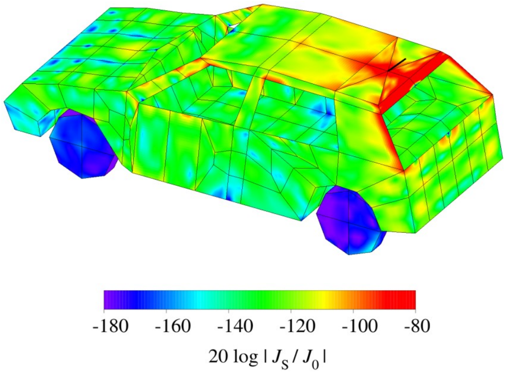
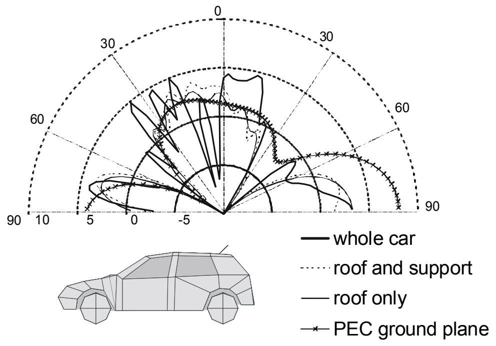


Fig.4. MoM simulated current distribution over a vehicle with an antenna at 860 MHz.

As an example of antennas with curved surfaces, consider a system of wire monopoles attached to a 22-cm high metallic cylinder at 833 MHz [3]. The system is analyzed in two configurations: (1) with a single 12-cm monopole antenna attached to the cylinder and (2) with an 8-cm driven monopole (antenna) and 44-cm parasitic monopole attached to the cylinder. The cylinder is modeled using 32 quadrilateral surface elements of the 2nd geometrical order (Fig.2) [1]. The results for the antenna impedance (Fig.2) and the radiated far field (Fig.3) obtained by the higher-order MoM and only 62 unknowns are compared with the results obtained by the low-order MoM with 986 unknowns from [3], and a very good agreement of the two sets of results is observed.

Another example of higher order MoM computation is a pigtail $3\lambda/4$ oblique-monopole cellular-telephone band antenna at 860 MHz mounted on the roof of a vehicle. Shown in Fig.4 is the simulated current distribution over the car body. Fig.5 shows the computed radiation pattern of the antenna for different levels of geometry details modeled. In the full-body model, the total number of unknowns is only 3081 and the CPU time only 145 seconds on a relatively modest PC (AMD XP-1700+ with 512 MB of RAM).

The next example considers a cubical metallic scatterer and demonstrates the improved orthogonality properties of higher-order hierarchical MoM basis functions constructed from ultraspherical and Chebyshev orthogonal polynomials on bilinear quadrilaterals [4]. Fig.6 shows that the use of ultraspherical/ultraspherical, ultraspherical/Chebyshev, and Chebyshev/Chebyshev basis functions provides the reduction in the condition number of the MoM matrix of approximately 1100, 13000, and 29000 times, respectively, as compared to regular polynomials at the highest frequency considered.



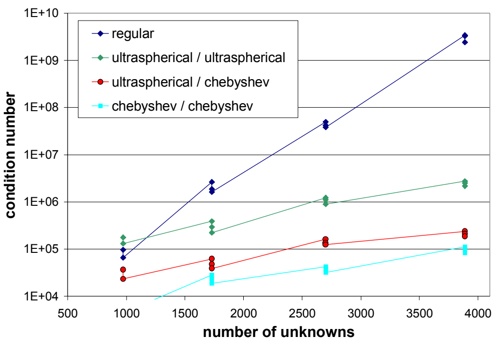
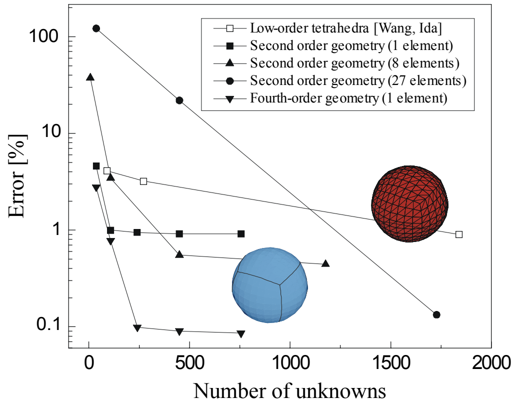


Fig.5. MoM simulated radiation pattern for a vehicle with a pigtail antenna at 860 MHz - different levels of geometry details modeled.

Fig.6. Condition number of the MoM matrix for a cubical scatterer, for four classes of higher-order hierarchical basis functions.

As the first example of higher-order FEM modeling, Fig.7 shows the results for the dominant eigenmode of an air-filled spherical metallic cavity obtained by a low-order FEM technique [5] and four higher-order FEM models [2]. In the higher-order FEM approach, the sphere is first modeled by a single curved hexahedron (note that this is literally an entire-domain FEM model) of the 2nd and 4th geometrical order, respectively, and field-approximation orders are varied from 3 to 7 in both solutions (*p*-refinement), and then by 8 and 27 triquadratic (second-order) hexahedral elements, with the field-approximation orders being varied from 1 to 4 and from 1 to 3, respectively, in all directions (combined *hp*-refinement). We observe excellent accuracy and fast convergence of higher-order models and their superiority over the reference low-order solution, as well as a significant additional improvement in accuracy as a result of using geometrical modeling of the 4th order.



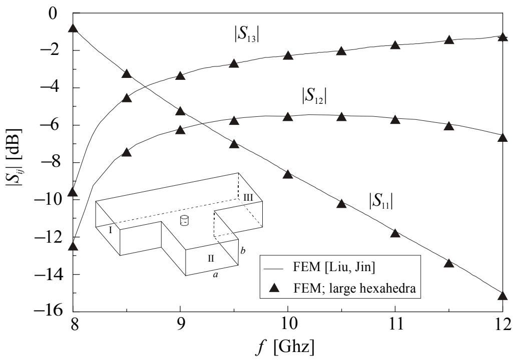


Fig.7. Higher-order and low-order FEM eigenmode computation of a spherical cavity.

Fig.8. FEM analysis of an *H*-plane waveguide T-junction with a cylindrical PEC post.

Consider next an *H*-plane waveguide T-junction loaded with a “partial-height” cylindrical post [6]. In our higher-order, large-domain FEM analysis, a simple mesh constructed from only 8 large curvilinear (3 trilinear and 5 triquadratic) hexahedra with field-approximation orders ranging from 2 to 5 in different directions in particular elements is used. This results in a total of 1,245 unknowns. Fig.8 shows *S*-parameters of the junction. The results obtained by the higher order hexahedral FEM modeling are compared with those obtained by another higher order technique and 6,471 unknowns [6]. We observe an excellent agreement between the two sets of results, the reduction in the number of unknowns with the presented method being about 80% when compared to the reference solution [6].

As an example of higher order hybrid MoM-PO modeling, consider a 14-GHz parabolic reflector antenna 51.44 cm in diameter fed by a pyramidal horn (Fig.9). The horn is modeled by 28 flat quadrilaterals with current approximation orders ranging from 2 to 8 for different patches. The reflector surface is modeled using 420 curved quadrilaterals of the second geometrical order with the fifth-order current approximation for all of the quadrilaterals. Fig.10 shows MoM-PO simulated far field patterns in the 45-degree plane. These results have been found to be in an excellent agreement with the results obtained by the pure MoM. The number of unknowns is 5458 in both methods, and the CPU time 809 seconds for the pure MoM and only 31.4 seconds for the MoM-PO (on a PC AMD XP-1700+), which makes the hybrid analysis more than 25 times faster when compared to the rigorous (full MoM) analysis.

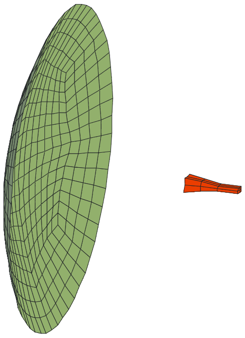


Fig.9. MoM-PO model of a parabolic reflector antenna fed by a pyramidal horn (horn is in the MoM-region and reflector in the PO-region).

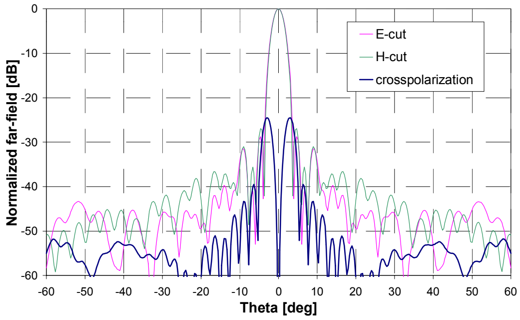


Fig.10. MoM-PO simulated co-polarized and cross-polarized far field patterns in the 45-degree plane of the antenna system in Fig.9.

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