Rigorous EM Modeling of Cars and Airplanes

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Abstract: *Rigorous electromagnetic (EM) modeling of cars and airplanes on a PC by using large-domain method of moments is presented. A Golf GL is analyzed, with different wire antennas mounted on or situated in it, at 98 MHz (FM) and 860 MHz (cellular telephone). A Boeing 737-300 is analyzed in both the scatterer (RCS) and the antenna mode of operation at 100 MHz (low-frequency radar and aircraft navigation). It is demonstrated that an accurate and efficient rigorous EM-field computational method must be considered as an indispensable tool for the analysis and design of wireless communication systems that include cars and airplanes.*

1. Introduction

Modern radio, wireless, and satellite communication systems often include vehicles (cars, airplanes, helicopters, spacecraft, etc.). From the electromagnetic (EM) point of view, these vehicles are 3D objects consisting predominantly of metallic and linear-dielectric parts of complex shapes, which are excited by EM waves produced by some antennas. Let us call these antennas the primary radiators. When a primary radiator is very close to a vehicle (e.g., antennas mounted on vehicles or situated inside them), the entire system (primary radiator plus vehicle), or a significant part of it, acts as a transmitting antenna. When the distance between a primary radiator and a vehicle is, on the other hand, very large with respect to both the wavelength of the excitation, λ, and maximal vehicle dimension, the vehicle represents a scatterer (with no return influence on the primary radiator). Finally, a receiving antenna case may be treated in the same way as a transmitting one, due to reciprocity.

This is the most challenging and extremely difficult general radiation/scattering EM problem, which can be approximately solved only by means of numerical electromagnetics. When the size of the vehicle is neither very large nor very small compared to λ, asymptotic (high- and low-frequency) numerical methods cannot be used to approach the problem. In the intermediate size region, often called the resonance region, a rigorous numerical solution of EM field equations is required. A rigorous approach is indispensable also for "locally detailed" electrically very large vehicles in the antenna mode of operation (e.g., for the airplanes with electrically small or medium-sized communication antennas on them at high frequencies), at least for the treatment of "hot parts" of such structures (e.g., of wings with antennas).

2. Rigorous Numerical EM Analysis

By the rule, partial differential-equation (PDE) methods, such as finite-difference and finite-element methods, require supercomputers even for the simplest 3D open-region problems. In this paper we therefore adopt an integral-equation (IE) formulation for rigorous EM modeling of cars and airplanes using a personal computer (PC). We utilize as unknown quantities in integral equations surface equivalent electric and magnetic currents over metallic and dielectric surfaces. Boundary conditions for the tangential components of the electric and magnetic field vectors are stipulated to be satisfied on the surfaces.

Within practically all the existing IE methods, surfaces are modeled by planar rectangles and triangles (a brief review of methods can be found in [1]). The components of the electric and magnetic surface current density vectors are commonly approximated by 2D pulse functions and rooftop functions. As the consequence of the adopted low-order current approximation, these methods imply that the surface elements must be electrically very small (on the order of $\lambda^2/100$ in area), and result in a very large number of unknowns to obtain results of satisfactory accuracy, with all the associated problems.

As the basic surface element we adopt a bilinear quadrilateral [1-2], shown in Fig.1. This, very flexible, quadrilateral is defined uniquely by its four vertices, that can be positioned arbitrarily in space. Its edges and all parametric coordinate lines are straight, but its surface, a bilinear surface, is generally curved. The quadrilateral (surface) can be described analytically by a bilinear equation of two local parametric (generally

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non-orthogonal) coordinates, u and v. We approximate the u- and v-components of electric and magnetic current density vectors over the surface by 2D polynomials in u and v [1-2]. The polynomial degrees can be high, enabling electrically relatively large surface domains (on the order of 2λ in each dimension). Consequently, the resulting number of unknowns for a given problem is greatly reduced (for more than an order of magnitude) when compared with small-domain solutions.

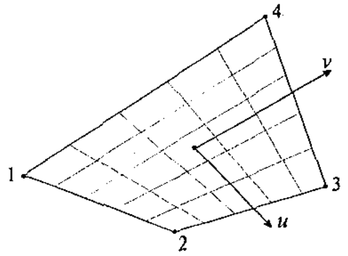

Fig.1. Bilinear quadrilateral-surface

With such an efficient tool for large-domain surface EM modeling we are able to rigorously analyze a wide range of vehicles on even a PC. In this paper we present realistic EM models of a car (Golf GL) in the antenna mode of operation and an airplane (Boeing 737-300) in both the scatterer and the antenna mode of operation, which are of interest to a broad radio and wireless audience.

3. Radiation by Golf GL

In this section, we analyze several communication wire antennas mounted on or situated in a Golf GL. Fig.1 shows a photograph and the simulated geometrical model of the car.

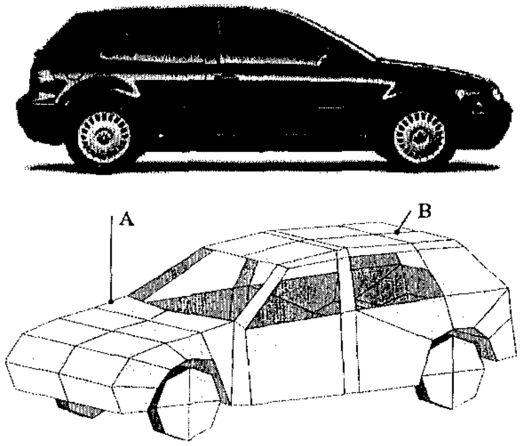

Fig.2. Photograph and simulated geometrical model of a Golf GL. The model is constructed from 160 bilinear surface elements.

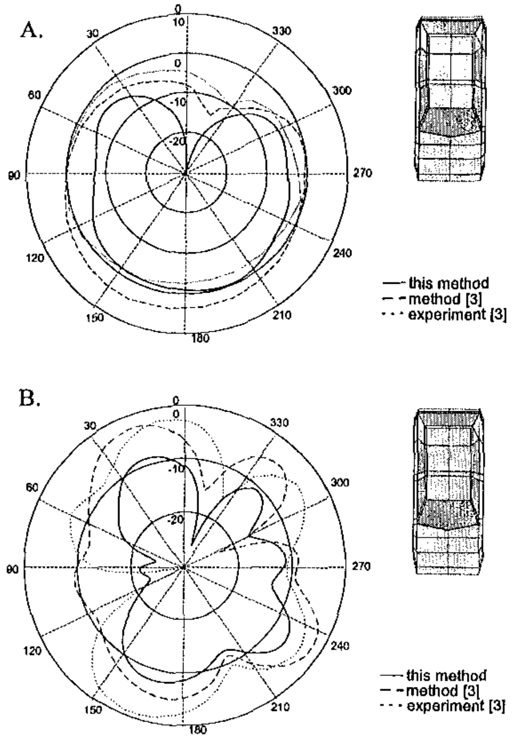

Fig.3. Radiation pattern in the azimuth plane (at 88° elevation angle) of the fender-whip antenna in Fig.2.A for (A) theta (vertical) and (B) phi (horizontal) polarization. The large-domain MoM simulation results are compared to both the experimental results and the small-domain electromagnetic-surface-patch (ESP) MoM simulation results for a similar car [3]. All the results are normalized to the corresponding theta-polarization data for the reference rooftop monopole antenna.

Consider first a FM fender-whip $\lambda/4$ monopole antenna (Fig.2.A) at 98 MHz. Fig.3 shows the radiation pattern in the azimuth plane (at 88° elevation angle) of the antenna for (A) theta (vertical) and (B) phi (horizontal) polarization of the electric-field vector. The results obtained by the large-domain MoM code are compared to both the experimental results and the small-domain (low-order current approximation) MoM simulation results for a similar car [3]. All the results are normalized to the corresponding theta-polarization results for the reference rooftop vertical-monopole antenna. We observe satisfactory agreement between our results and the two sets of results reported in [3], having in mind the differences between a Golf GL and the car model simulated and measured in [3].

The Golf GL model is $2.4\lambda^2$ large in area at 98 MHz and complex in shape. The total number of unknowns for the approximation of currents in the large-domain MoM simulation amounts to 505. The CPU time required for the analysis, including the postprocessing, is only 72 seconds on a PC AMD-K6 266 MHz with

128 MB of RAM memory. Note that the CPU time reported in [3] for a similar example (backlite heater-grid antenna) was 512 seconds with a Cray Y-MP8/864 computer.

Consider next a pigtail $3\lambda/4$ oblique-monopole antenna mounted on a Golf GL (Fig.2.B) and a $\lambda/2$ dipole antenna situated inside the car (about the car center) at 860 MHz (note that 824-894 MHz is the cellular-telephone band in the United States). The area of the Golf model is very large at 860 MHz (approximately $185\lambda^2$). The total number of unknowns in the large-domain simulation with using symmetry is 3,081, and the CPU time only 100 minutes on a PC AMD-K6 266 MHz.

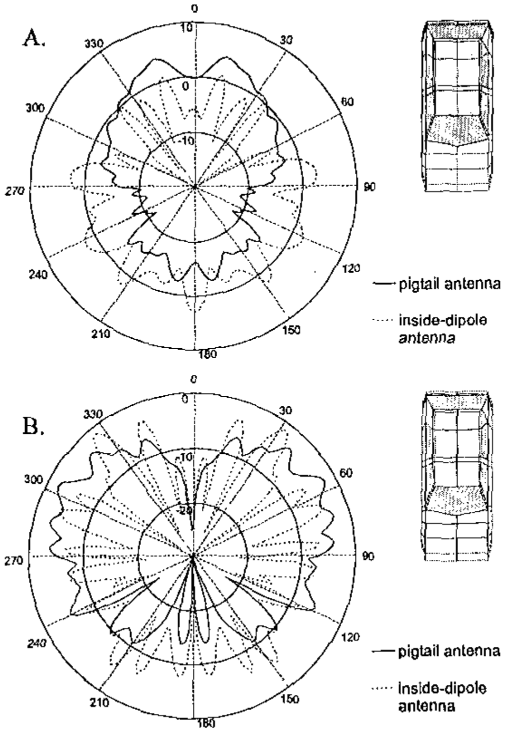

Fig.4. Simulated radiation pattern in the azimuth plane (at 88° elevation angle) of the pigtail antenna in Fig.2.B and a dipole antenna situated inside the car for (A) theta (vertical) and (B) phi (horizontal) polarization, normalized to the vertical-polarization pattern of the rooftop vertical-monopole antenna.

Shown in Fig.4 is the simulated radiation pattern in the azimuth plane (at 88° elevation angle) of the pigtail antenna and the inside-dipole antenna, for (A) theta (vertical) and (B) phi (horizontal) polarization of the electric-field vector. The results are normalized with respect to the corresponding vertical-polarization data for the rooftop vertical-monopole antenna. We see many deep nulls in the pattern of the dipole antenna (approximating an outdoor mobile-telephone integrated antenna) situated inside the car, which are due to reflections by the car body. An externally mounted antenna, such as a pigtail antenna, is therefore a preferable solution for improving car mobile telephone system performances.

4. Scattering and radiation by Boeing 737-300

In this section, we analyze a Boeing 737-300 in both the scatterer and the antenna mode of operation at 100 MHz (frequency band used in low-frequency radar and aircraft navigation systems). This is one of today's most popular commercial airplanes. Fig.5 shows a photograph and the simulated geometrical model of the airplane.

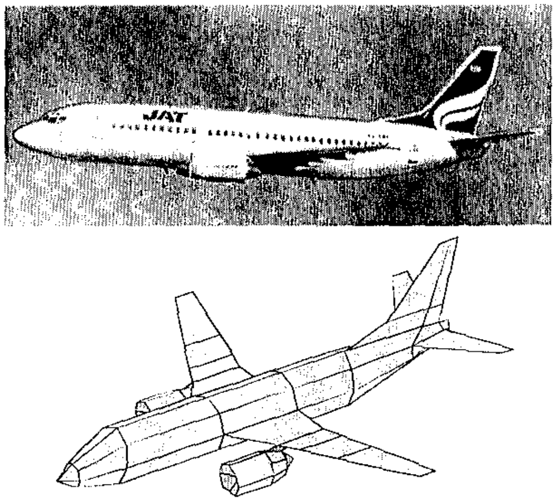

Fig.5. Photograph and simulated geometrical model of a Boeing 737-300. The model consists of 126 bilinear surface elements.

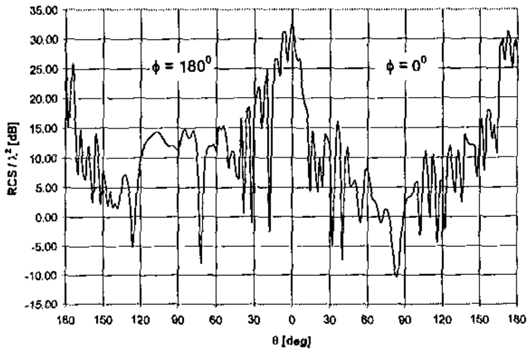

Fig.6. Simulated radar cross-section of the aircraft in Fig.5 for various directions of the plane-wave incidence in the plane of the aircraft symmetry. The angles $\theta = 0°$, $\theta = 180°$, ($\theta = 90°$; $\phi = 180°$), and ($\theta = 90°$; $\phi = 0°$) correspond to the directions toward the aircraft top, bottom, "nose", and "tail", respectively. The RCS is normalized to λ^2.

Fig.6 shows the simulated radar cross-section (RCS) of the aircraft in Fig.5 for various directions of the plane-wave incidence in the plane of the aircraft symmetry. As expected, the largest RCS is obtained for the directions defined by $\theta = 0°$ (top of the aircraft) and $\theta = 180°$ (bottom of the aircraft).

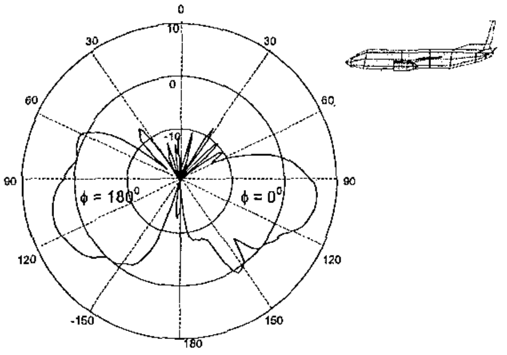

Fig.7. Simulated gain in the elevation plane (plane of the aircraft symmetry) of the 50-cm vertical monopole antenna attached to the bottom of the aircraft model in Fig.5.

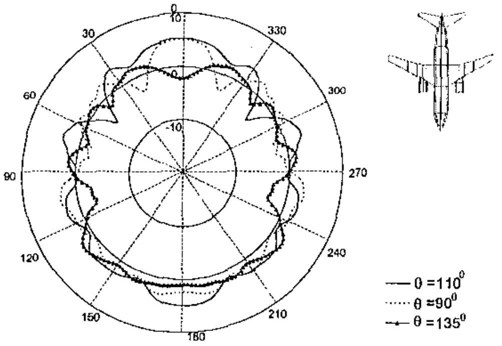

Fig.8. Simulated gain in the azimuth (horizontal) plane of the 50-cm vertical monopole antenna attached to the bottom of the aircraft model in Fig.5 for three different elevation angles.

Shown in Fig.7 is the simulated gain pattern in the elevation plane (plane of the aircraft symmetry) of the 50-cm vertical monopole antenna attached to the bottom of the aircraft model in Fig.5. Fig.8 shows the simulated antenna gain pattern in the azimuth (horizontal) plane for three different elevation angles. We observe the highest gain for 110° (in the airplane's forward direction) and 100° (in the back direction) elevation angles. As expected, the radiation into upper half-space is low. The azimuth pattern for $\theta = 110°$ has nulls in the directions defined by $\phi = 50°$ and $\phi = 310°$, which are the directions toward the aircraft's engines.

At 100 MHz, the total area of all the bilinear surfaces in the Boeing 737-300 simulated model is about $60\lambda^2$. The total number of unknowns for the approximation of currents in the scattering simulation using symmetry amounts to 1546 (1552 for the airplane with the antenna), and the CPU time required for the analysis to only 12 minutes (12.5 minutes for the antenna mode of operation) on a PC AMD-K6 266 MHz. We are not aware of any other rigorous EM method/software that can handle a vehicle of similar electrical size and complexity on a PC (see also Section 3 with the $185\text{-}\lambda^2$ large Golf GL model at 860 MHz). For example, the number of finite-elements used for the EM modeling of a much smaller airplane reported in [4] is 201,556 at 100 MHz, and the required CPU time is as large as 5.4 hours using four DEC-ALPHA workstation processors.

5. Conclusions

This paper presents a rigorous electromagnetic modeling of cars and airplanes on a PC. A Golf GL is analyzed, with wire antennas mounted on or situated in it, at 98 MHz and 860 MHz. A Boeing 737-300 is analyzed in both the scatterer (RCS) and the antenna mode of operation at 100 MHz. It is demonstrated that an efficient and accurate EM-field computational method, such as the large-domain (high-order current-approximation) MoM developed by the authors of the present paper, must be considered as an indispensable tool for the analysis and design of wireless communication systems that include cars and airplanes.

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