EMC analysis in a living environment by parallel finite element method

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Abstract— **This paper describes an evaluation of electromagnetic compatibility based on full-wave analysis of electromagnetic fields using a parallel finite element method. The environment chosen is the interior of a commuter train. A train containing seats, handrails and four human bodies is precisely modeled using a large-scale finite element mesh with Nedelec elements and about 21 million degrees of freedom. The results show that the environmental impact of electromagnetic fields due to cellular phone use in the train can be successfully evaluated.**

I. INTRODUCTION

We have been actively investigating numerical techniques for analysis of the impact of electromagnetic fields in the frequency range of several MHz to several GHz in living environments. In such a risk assessment, digital data regarding the electromagnetic field intensity need to have the highest possible resolution. Also, the entire living environment used in the analysis needs to be precisely modeled. For this reason, the model should include different materials such as dielectrics and metals with different shapes and sizes. Moreover, in order to ensure sufficient calculation accuracy, it is necessary to set the maximum element length to 1/10 of the wavelength of the electromagnetic field. Due to the complexity of such models, intensive calculations are required in the simulations. Currently, we are conducting research on large-scale finite element analysis (FEA) for high-frequency electromagnetic fields using parallelization techniques based on the iterative domain decomposition method (IDDM). The conjugate orthogonal conjugate gradient (COCG) method is applied to solve the interface problem of the IDDM. We have previously reported the results of numerical analyses involving about 100 million complex degrees of freedom (DOF) based on the formulation of the E Method [1]. In the present paper, we discuss the methodology of electromagnetic compatibility (EMC) assessment based on the International Council on Non-ionizing Radiation Protection (ICNIRP) guidelines [2] using a commuter train model. To the best of our knowledge, there have so far been no reports on the use of large-scale full environment models involving complex shapes and different materials to tackle EMC problems.

II. EMC CRITERIA

Based on many previous studies, several sets of EMC guidelines have been developed for both working environments and ordinary living environments. The ICNIRP guidelines are among the most widely used, and contain some of the most rigorous criteria. Therefore, in the present study, we employ criteria based on the ICNIRP guidelines to carry out an assessment of the environmental impact of electromagnetic radiation. The basic restrictions for exposure of the general public to electric and magnetic fields up to 300 GHz are shown in Table I [2].

TABLE I
ICNIRP GUIDELINES FOR GENERAL PUBLIC EXPOSURE

Frequency range	Electric field (V/m)	Magnetic field (A/m)
0-1 Hz	—	3.2×10^4
1-8 Hz	10,000	$3.2\times10^4/f^{1/2}$
8-25 Hz	10,000	5,000/f
0.025-0.8 kHz	250/f	5/f
0.8-3 kHz	250/f	6.25
3-150 kHz	87	6.25
0.15-1 MHz	87	0.92/f
1-10 MHz	$87/f^{1/2}$	0.92/f
10-400 MHz	27.5	0.092
400-2000 MHz	$1.375\ f^{1/2}$	$0.0046\ f^{1/2}$
2-300 GHz	61	0.20

Note:
1. f is the frequency in the units shown in the first column.

III. FINITE ELEMENT FORMULATION

A. Vector Wave Equations

Let Ω be a domain with a boundary $\partial\Omega$. The vector wave equations [1] which describe an electromagnetic field with a single angular frequency ω (rad/s) are derived from Maxwell's equations containing the displacement current. The vector wave equations describing an electric field $\mathbf{E}$ (V/m) are given by (1a) and (1b) below, for a current density $\mathbf{J}$ (A/m^2), and assigning j as an imaginary unit:

$$\mathrm{rot}\left(1/\mu\,\mathrm{rot}\,\mathbf{E}\right)-\omega^2\varepsilon\mathbf{E}=j\omega\mathbf{J} \quad \text{in } \Omega\,, \tag{1a}$$

$$\mathbf{E}\times\mathbf{n}=\mathbf{0} \quad \text{on } \partial\Omega\,, \tag{1b}$$

$$\mathbf{J}=\sigma\hat{\mathbf{E}}\,. \tag{1c}$$

Permittivity and permeability are given by ε (F/m) and μ (H/m), respectively. In this formulation, the permittivity has a complex value $\varepsilon=\varepsilon'+\sigma/j$. The electric field $\hat{\mathbf{E}}$ at known points is then substituted into (1a) from (1c), where the electrical conductivity is denoted as σ. By solving (1a) under the boundary condition in (1b), we calculate the electric field $\mathbf{E}$. For an absorbing boundary (ABC) $\partial\Omega_{\mathrm{ABC}}$:

$$(\mathrm{rot}\mathbf{E})\times\mathbf{n}-j\omega\sqrt{\varepsilon_0\mu_0}\,(\mathbf{E}\times\mathbf{n})\times\mathbf{n}=0 \quad \text{on } \partial\Omega_{\mathrm{ABC}}\,. \tag{2}$$

The first-order ABC to account for the Sommerfeld radiation condition is given by (2).

B. E Method

Next, we describe the finite element discretization. The electric field **E** is approximated with Nedelec elements (edge elements) [1], [3]. The finite element approximation is performed as follows [1].

Find $\mathbf{E}_h$ such that

$$\left(1/\mu\ \mathrm{rot}\mathbf{E}_\mathbf{h}, \mathrm{rot}\mathbf{E}_\mathbf{h}^*\right)_\Omega - \left(\omega^2\varepsilon\mathbf{E}_\mathbf{h}, \mathbf{E}_\mathbf{h}^*\right)_\Omega + \left(j\omega\sqrt{\varepsilon_0/\mu_0}\mathbf{E}_\mathbf{h}\times\mathbf{n}, \mathbf{E}_\mathbf{h}^*\times\mathbf{n}\right)_{\partial\Omega_{ABC}} = \left(j\omega\mathbf{J}_\mathbf{h}, \mathbf{E}_\mathbf{h}^*\right)_\Omega \qquad (3)$$

where $(\cdot,\cdot)_\Omega$ denotes the complex valued L^2-inner product defined on Ω. Here, $\mathbf{J}_\mathbf{h}$ is the electric current density approximated by the conventional piecewise linear tetrahedral elements.

C. Parallelization

We introduce the IDDM for parallelization of high-frequency problems using the E method. The IDDM is implemented in a parallel computing environment using the hierarchical domain decomposition method (HDDM). In the present paper, we use the P-mode, which is one of the parallel data handling types of the HDDM [3], [4].

IV. NUMERICAL EXAMPLES

As an example of a real-world EMC problem, we model the internal environment of a commuter train with four phantoms of human bodies inside [5]. In addition to the human bodies, the interior of such a train contains many materials forming structures such as reflecting barriers, walls, handrails, and seats, and these are modeled as dielectrics and metals with different permittivities and conductivities. The properties of the materials used in this analysis are shown in Table II. The electromagnetic field distribution may change based on the geometric arrangement among these materials. Therefore, it is necessary to correctly reproduce the real environment. Some dielectrics such as plastic parts, and some reflective parts such as metals are modeled precisely in this numerical model. The dimensions of the analysis model are shown in Figs. 1(a) and (b) and the CAD model is shown in Fig. 1(c). The model has a length of 3.3 m, a width of 3.4 m, and a height of 3.25 m. It is assumed that the four persons are talking on cellular phones. The electromagnetic field sources are dipole antennas that imitate the cellular phones. In this analysis, the phantom composition is approximated by physiological saline, and the seats are considered to be plastic. The maximum element length is 0.02 m, and the number of complex DOF is 21,860,675. The radiation frequency is set to be 800 MHz, for which the ICNIRP guidelines stipulate a maximum electrical intensity of 38.9 V/m. The antenna is assumed to have ideal voltage and current sources of 1 V and 0.8 A, respectively. The EMC in the commuter train is evaluated by comparing the numerical results with the criteria specified in the guidelines. The computations are performed on a 20-node (80-core) PC cluster (Intel Core i7 940; 2.93 GHz; L2 256 KB; L3 8 MB; Quad Core; QPI 4.8GTs) with 12 GB RAM per node. The simulation statistics are shown in Table III. The simulated electric field within the train is shown in Fig. 2. Peaks are observed at the locations of the cellular phones. The maximum electric field strength is found to be 5.12×10^{-1} V/m within the train, which is lower than the value specified in the guidelines.

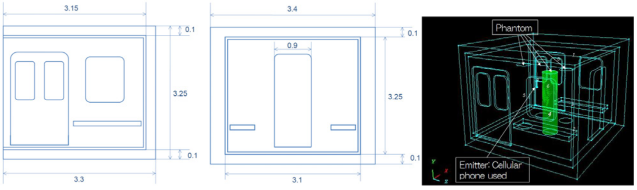
We are currently undertaking a more detailed environmental impact assessment, and the results will be shown at the conference.

TABLE II
MATERIAL PROPERTIES

Materials	Permittivity (F/m)	Conductivity (S/m)
Air	8.854×10^{-12}	–
Seat	7.083×10^{-10}	0.52
Car body	7.083×10^{-10}	4.0×10^{7}
Human bodies	7.083×10^{-10}	0.52

TABLE III
SIMULATION STATISTIC

No. of Elements	18,652,438
No. of DOF	21,860,675
Platform	20-node PC cluster with Intel Core i7 940 2.93 GHz
No. of cores	80
Main memory per node	12 GB
Elapsed time (sec)	16,488



(a) Side view (b) Cross section (c) CAD model

Fig. 1. Commuter train model (units: m).

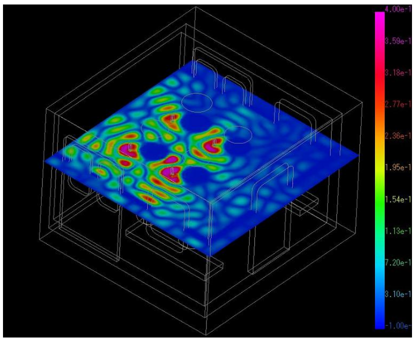


Fig. 2. Electric field in the commuter train.

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