Uncertainty Quantification of Human Body Exposure by Low-Frequency Magnetic Fields Using a Monte-Carlo Approach on GPUs

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Abstract

Numerical simulations are used to determine electric fields induced by low-frequency magneto-quasistatic fields into exposed human bodies. One of the utilized numerical methods is the Co-Simulation Scalar-Potential Finite Difference scheme that requires the magnetic flux density distribution, the field frequency, and the electrical conductivities of the body tissues as inputs. All of these quantities are subject to errors. New advances in the implementation and execution time of this numerical simulation method on Graphics Processing Units allow to calculate the body-internal electric field strength within seconds. One million simulations require 11.3 hours on 40 NVIDIA A100 GPUs, offering the option to use a Monte-Carlo approach to determine the uncertainty of the body-internal electric field strength.

1 Introduction

Wireless power transfer (WPT) systems, i.e., inductive charging systems, consist of a primary coil, which is driven by low-frequent currents and emanates low-frequent magnetic fields, and a secondary coil. The magnetic flux through the secondary coil induces a voltage that can be used to charge batteries of mobile phones on a small scale up to larger scales like that of cars or busses. For vehicles, the transmitted power is ideally in the range of tens to hundreds of kilowatts to charge batteries quickly. Stray magnetic fields can escape the WPT system, are guided by electrically conductive parts, and possibly expose humans in or next to the vehicle.

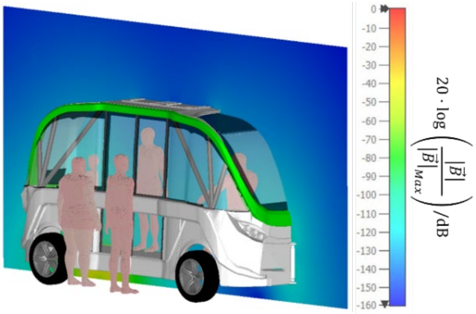

Figure 1: Exemplary magnetic field exposition in the MILAS project.

These low-frequent magnetic fields induce electric fields in the conductive human body tissues that can potentially be harmful. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1] introduced limits on the body-internal electric field strength. The ICNIRP recommends to use human models made of voxel with $2\ \mathrm{mm}$ edge lengths in every spatial direction. To remove numerical artefacts, the highest 1% of the electric field strength values are neglected. These numerical exposure simulations with millions of voxels can be computationally expensive. Over the last years, advances in using high performance Graphics Processing Units (GPUs), parallel computing allowed to enhance the simulation speed.

However, uncertainties of the calculated electric field strength values need to be determined. These can be induced by the numerical simulation model itself, the numerical accuracy of computer calculations in general, and the uncertainty of the input parameters.

This work focuses on the latter and uses a Monte-Carlo approach to determine electric field strength uncertainty induced by the input parameters as, for example, the electrical conductivity of the body tissues.

2 Approach

In this work, the Co-Simulation Scalar-Potential Finite Difference (Co-Sim. SPFD) scheme [2] is used. The attenuating effect of the human body onto the exposing magnetic field can be neglected as well as displacement currents in the human body. The wavelength at a typical WPT system frequency of 85 kHz is about 3.5 km and therefore, magneto-quasistatic conditions apply.

2.1 Co-Simulation Scalar Potential Finite Difference

The magnetic flux density $\vec{B}$ exposing the human body can be derived from simulations or measurements. It is used as input to extract the magnetic vector potential $\vec{A}$

$$\vec{B} = \nabla \times \vec{A}, \tag{1}$$

via the tree-cotree gauging technique in the discrete formulation [3]. This magnetic vector potential serves as input to the linear Poisson system of the SPFD scheme [4]

$$\nabla \cdot [\sigma \nabla \psi] = \nabla \cdot \left[-j\omega\sigma \vec{A}\right], \tag{2}$$

with the electrical conductivity σ, the angular frequency $\omega = 2\pi f$, and is solved for the scalar conduction potential ψ. In the following iteration step, the electric field intensity $\vec{E}$ can be calculated with

$$\vec{E} = -\nabla\psi - j\omega \vec{A}. \tag{3}$$

The human body models consist of a voxel structure as recommended by the ICNIRP; accordingly, the Finite Integration Technique [5] is used to discretize equations (1)-(3).

2.1 Monte-Carlo Uncertainty Quantification

All input quantities into the Co-Sim. SPFD scheme contain errors. Currents in WPT systems are subject to fluctuations as well as the magnetic flux density magnitude. One of the largest uncertainties arises from the electrical conductivity of the tissues, that can vary by orders of magnitude (e.g. dry and wet skin).

Using the latest generations of GPUs and efficient Co-Sim. SPFD implementations, equations (1)-(3) can be solved within seconds. This allows the use of Monte-Carlo methods to derive an electric field strength uncertainty from the complex set of input variables.

All input parameters are varied using a normal distribution with their respective uncertainties, i.e., the frequency has an uncertainty of 0.01%, the electrical conductivity of all tissues 15% and the magnetic flux density amplitude 4%. All variations are preliminary.

This approach allows to combine all gathered uncertainties into one electric field strength uncertainty in the frame of the Co-Sim. SPFD scheme. It does not quantify the uncertainty of the scheme itself.

3 Preliminary Results

An upright standing human model with the ICNIRP recommended voxel resolution of $2 \times 2 \times 2\ \mathrm{mm}^3$ is exposed by a homogeneous magnetic flux density with an amplitude of $27\ \mu\mathrm{T}$ (RMS) perpendicular to the coronal plane at a frequency of $85\ \mathrm{kHz}$. All input quantities are varied one million times in their respective parameter distributions to determine the maximum body-internal electric field strength and the 99th percentile. Using 40 NVIDIA A100 GPUs, the calculation time for 1 million simulations with 8.9 million degrees of freedom (2) takes approximately 11.3 hours.

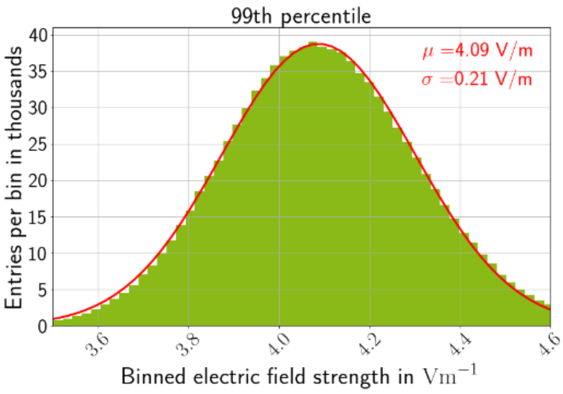

Figure 2: Uncertainty distribution of the 99th percentile of the body-internal electric field strength.

The electric field strength distribution of the 99th percentile is shown in Figure (2). The distribution agrees well to a normal distribution. The uncertainty of the 99th percentile of the electric field strength is about 5%.

4 Conclusion and Outlook

The Monte-Carlo approach to determine the uncertainty of the body-internal electric field proved to be feasible on modern GPUs with the SPFD scheme. Modern GPU generations were able to perform 1 million simulations in less than 12 hours at 8.9 million degrees of freedom.

The full paper will be extended with additional human models at different voxel resolutions, an additional uncertainty of the spatial direction of the magnetic flux density, and a more sophisticated, tissue specific, uncertainty model. Besides, benchmarks of different GPU generations and the evolution of the simulation time development will be given.

Acknowledgements

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