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A Web-Accessible Tool for 2D Analytical Solutions of Electromagnetic Fields in Concentric Cylinders

Giuseppe Carluccio, Ph.D.
Center for Biomedical Imaging, Department of Radiology New York University Grossman School of Medicine
New York, USA
giuseppe.carluccio@nyulangone.org

Eros Montin, Ph.D.
Center for Biomedical Imaging, Department of Radiology New York University Grossman School of Medicine
New York, USA
eros.montin@nyulangone.org

Christopher Collins, Ph.D.
Center for Biomedical Imaging, Department of Radiology New York University Grossman School of Medicine
New York, USA
c.collins@nyulangone.org

Riccardo Lattanzi, Ph.D.
Center for Biomedical Imaging, Department of Radiology New York University Grossman School of Medicine
New York, USA
riccardo.lattanzi@nyulangone.org

***Abstract*—In this work we present a web-accessible tool that provides a bidimensional analytical solution of the electric and magnetic fields generated by an infinitely long conducting wire, and scattered by two concentric infinitely long cylinders. The application will be available on the portal Cloud MR where it can be connected to other applications to estimate the impact of the electromagnetic field distribution on images and patient heating for magnetic resonance imaging (MRI) experiments.**

***Keywords*—2D Analytical Solution, Cylinder, MRI, Cloud Computing, Web-accessible**

I. Introduction

In Magnetic Resonance Imaging (MRI) it is of great importance to estimate the distribution of the radiofrequency (RF) field B_1. Many MRI applications rely on RF field simulations, such as the optimization of coils for maximizing the transmit efficiency, SNR, or to assess RF safety. Although it is common to rely on numerical simulations for higher accuracy in presence of complex geometries such as human tissues having different values of permittivity and electrical conductivity, analytical solutions are still used to describe the distribution of RF fields using tissue-mimicking simple geometries. Specifically, the short computation time of the analytical solutions make them very suitable for optimization routines or even for training machine learning networks, where a significant amount of data is required, and the analytical solutions can describe with high accuracy the scattering of the fields[1-2].

In this work, we have developed a web-accessible solver that provides the bi-dimensional electric and magnetic fields distributions inside two concentric cylinders that are excited by infinitely long wires. The solver is designed to run without using local resources, and without the need to install additional software on local machines. It is included in Cloud MR [3], a hub of web-accessible applications where it can be connected to other apps to obtain synthetic MRI images from the calculated fields, and also compute the resulting temperature increase due to RF absorption.

II. Methods

A. Analytical Solution

The solver calculates the electric and magnetic fields in cylindrical coordinates for two concentric infinitely long cylinders with the fields generated by N infinitely long wires[4-8].

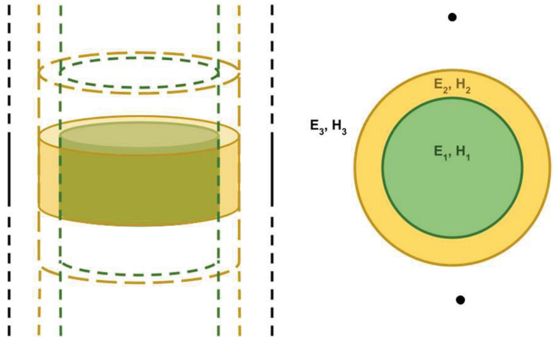

Fig. 1. Geometry of the problem. On the left, three-dimensional view of the conducting wires (black) and the two infinitely long concentric cylinders (yellow and green). On the right, axial view of the problem for two conducting wires.

The electric fields are parallel to the wires, and in the three regions (Fig. 1) they are given by the superposition of Bessel and Hankel functions: $E_1(r)$ represents the spatial distribution of the electric field in the inner cylinder, $E_2(r)$ the field in the outer shell, and $E_3(r)$ the field in the medium were the conducting wire is immersed.

$$E_1(r) = \sum_{m=-\infty}^{+\infty} a_m J_m(\beta_1 \rho) e^{jm\phi}$$
$$E_2(r) = \sum_{m=-\infty}^{+\infty} [b_m J_m(\beta_2 \rho) + c_m H_m^{(2)}(\beta_2 \rho)] e^{jm\phi} \quad (1)$$
$$E_3(r) = \sum_{m=-\infty}^{+\infty} d_m H_m^{(2)}(\beta_3 \rho) e^{jm\phi} - \sum_{n=1}^{N} \frac{\beta_3^2 I_n}{4\omega\epsilon} H_0(|\vec{\rho} - \overrightarrow{R_n}|$$

where $\beta_1, \beta_2, \beta_3$ represents the propagation constants in the three regions, ρ and ϕ are the cylindrical coordinates of the location r where the fields are computed, and R_n is the distance of the n[th] wire from the center of coordinates.

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The radial and angular components of the magnetic fields are derived from the electric fields according to:

$$
\begin{aligned}
H_\rho(r) &= -\frac{1}{j\omega\mu\rho}\frac{\partial E(r)}{\partial\phi} \\
H_\phi(r) &= \frac{1}{j\omega\mu}\frac{\partial E(r)}{\partial\rho}
\end{aligned} \tag{2}
$$

The expansion coefficients a_m, b_m, c_m, d_m in eq. (1) are calculated by enforcing the continuity of the tangential components of the electric and magnetic fields at the interfaces between different regions.

B. Graphical user interface

The graphical user interface (GUI) has been developed using the Cloud MR (http://cloudmrhub.com) framework. This framework allows developers and users to access software applications by means of a standardized web-based GUI, from which computations are run via Docker containers deployed locally or on the cloud.

As for other applications in Cloud MR, the GUI of the simulator is based on React.Js and is composed by three main tabs: Home, Set Up and Results. In the "Home" tab, users can manage their data and results files. In the "Set Up" tab, users can customize simulations by choosing the spatial resolution of the output image, the diameters of the cylinders along with the permittivity and conductivity.

Finally, in the "Results" tab, users can check the status of the simulation tasks and select the successfully completed ones to display. In this tab, SNR, and the fields can be analyzed by means of regions of interest.

III. Results And Discussions

Fig. 2 reports the distribution of the magnitude of the electric and magnetic fields when two wires positioned on the y-axis are used to generated the incident fields. The inner cylinder has a permittivity $\epsilon_{r,1} = 60$ and conductivity $\sigma_1 = 0.5$, while the outer shell permittivity $\epsilon_{r,2} = 70$ and conductivity $\sigma_2 = 0$.

This work can estimate the fields in cylindrical geometries for MRI applications, and it can be integrated with other web-accessible applications available on Cloud MR, providing a fully integrated environment to estimate the impact of the electromagnetic field distribution on MRI images and patient heating. Two concentric cylinders can represent, for example, the brain shelled by the skull, or also be used in the optimization process for applications involving the use of High-Permittivity Materials, such as a dielectric helmet recently published to improve both the transmit efficiency and the SNR [9]. For example, an analytical solution using shelled spherical geometries have shown promising results to select the optimum permittivity for a given thickness of the High-Permittivity material [10-11].

In addition, this work provides an easy solution for all the engineers involved in the development of devices with fields scattered by cylindrical geometries, non-necessarily related to MRI.

In future work, we plan to increase the number of concentric cylinders, and provide analytical solutions for other geometries.

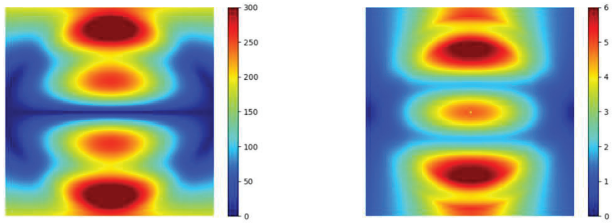

Fig. 2. For two conducting wires positioned the same axis and in phase, plot of the magnitude of the electric fields (V/m) on the left, and of the magnetic fields (A/m) on the right.

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