Approximation of MRI Scanner Stray Magnetic Field with Simplified Models

Zuzanna Krawczyk
Faculty of Electrical Engineering
Warsaw University of Technology
Koszykowa 75, Warszawa, Poland 00-662
Email: krawczyz@ee.pw.edu.pl

Jacek Starzyński
Faculty of Electrical Engineering
Warsaw University of Technology
Koszykowa 75, Warszawa, Poland 00-662
Email: jstar@ee.pw.edu.pl

***Abstract*—The paper proposes a new approach to compute the stray magnetic field of an MRI scanner. First the simplified model of MRI coils is created. The model should accurately simulate the stray magnetic field while being highly simplified and thus saving significantly the numerical resources. The simplified, analytical model is created by solving an inverse problem. Two inverse problem solvers: Levenberg-Marquardt and Particle Swarm Optimization are compared in this work.**

I. Introduction

MRI scanners, used commonly in contemporary medical practice, require sophisticated shielding (see Fig. 1) which protects sensitive electronic equipment from a stray magnetic field generated by main coils of the scanner and prevents from image degradation due to external sources of electromagnetic disturbances.

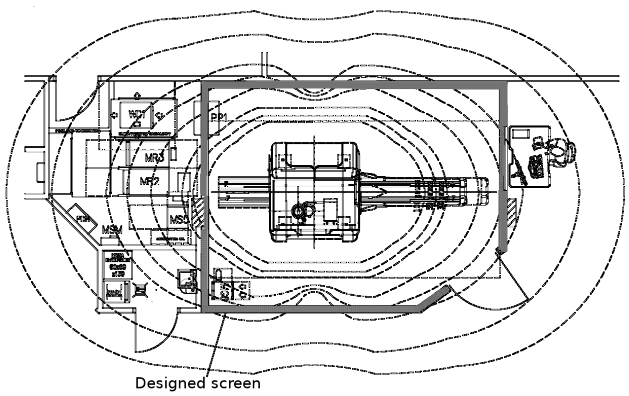

Fig. 1. Stray magnetic field of sample scanner. The lines of constant flux density module are presented for 100,50,30,10,5,...,0.5 gauss. The field is presented atop the scanner location plan and the designed screen boundaries, but is not influenced by those factors.

The screening system may be constructed on site, after the scanner is installed and the stray field can be measured. It is, however, not a budget-effective solution—it is always better to predict and avoid problems, than to fight with already existing ones.

A stray field of a bare scanner can usually be obtained from the manufacturer. All factors influencing the stray field distribution are normally known in advance and that knowledge can be used to build a numerical model of the scanner installation. Such model allows us to predict of the field distribution in a given installation and thus to design the shielding and/or active devices for field cancellation.

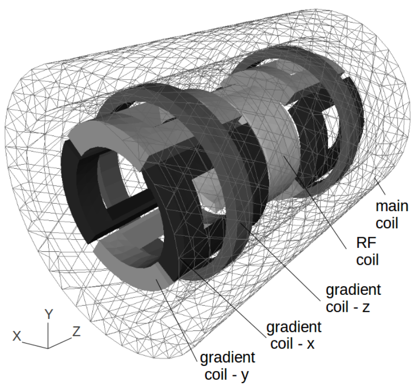

Fig. 2. Schematic diagram of an usuall MRI scanner coils: the main coil is shown as wireframe, gradient and RF coils are marked with different shadows of gray

The most complicated active part of an MRI scanner is a system of the scanner coils (see Fig. 2). Thus the greatest reduction of the model complexity can be obtained with accurate, but simplified model of this system. We can see, that the stray field shown in Fig. 1 is in generall symmetric and quite regular. Thus it should be possible to design a set od simple-shaped coils generating similar stray.

II. Simplified model of MRI coils

Authors approach to scanner approximation is based on the parallel implementation of exact formulae for magnetic induction due to cylindrical coil presented originally in [2]. Analytical expressions obtained in [2] are composed of one-dimensional integrals containing a combination of trigonometric and elementary functions. Parallel implementation of such expressions [1] was written in Python, employing Parallel Python and scientific libraries NumPy and SciPy to perform integration and faster vector operations.

III. Inverse problem

We want to approximate the stray field of the MRI scanner with a set of four coils: 2 base-coils and 2 additional correction coils arranged as in Fig 3. Magnetic field of such a system can be easily and quickly calculated with the authors program [1].

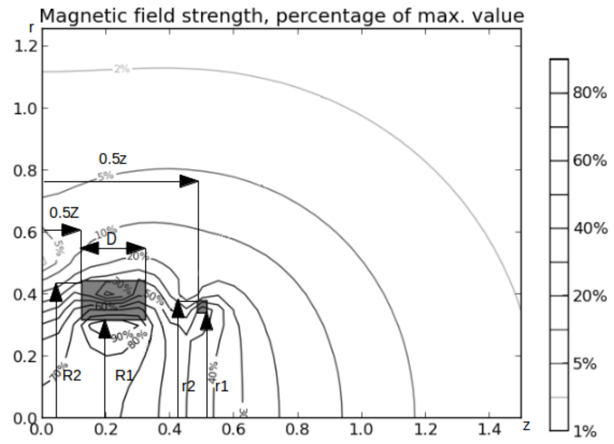

Fig. 3. Lines of constant magnetic induction for the model coils in the first quadrant of the (r,z) plane (note that z axis is horizontal)

The magnetic field of the system reassembles that of the stray field of the MRI, as is shown in Fig. 3. This fact indicates that a scanner can indeed be approximated by such coils, if we will be able to find the proper geometry. The 4-coil system can be described with 8 distinctive parameters: 1) the inner radius of the main coils R_1, 2) it's external radius R_2, 3) it's thickness D, 4) the distance between main coils Z and 5)-8) the respective parameters of the correction coils (r_1, r_2, d, z).

Knowing the values of the stray field (the magnitude of the flux density B) of an MRI scanner in several points: $[p_1, p_2, \ldots, p_n] \rightarrow [B_1, B_2, \ldots, B_n]$ and calculating field of approximating coils at the same points: $[p_1, p_2, \ldots, p_n] \rightarrow [\hat{B}_1, \hat{B}_2, \ldots, \hat{B}_n]$ we may formulate the inverse problem as a least square fit:

$$\min_{(R_1,R_2,D,Z,r_1,r_2,d,z)} F = \sum_{i=1}^{n} \left(B_i - \hat{B}_i \right)^2, \qquad (1)$$

with a minimal set of box-constrains for $R_1, R_2, D, Z, r_1, r_2, d$ and z. Other constrains may be necessary to avoid coil overlap.

Suspecting that the problem defined by (1) can have several local minima we have limited the fit to just a single line of magnetic field generated by the known system of 4 coils. Knowing the real solution we use it as a reference for those found by the optimizer.

For the purpose of this paper we use the 10% of the maximal value isoline– calculated for the following geometry (all values in meters): main coils: $R_1 = 0.3175$, $R_2 = 0.4445$, $D = 0.2$ and $Z = 0.244$, correction coils: $r_1 = 0.34$, $r_2 = 0.38$, $d = 0.03$ and $z = 0.485$. Such a choice does not limit the generality of our study. Due to the symmetries of the problem it can be reduced to a single quarter of the plane and the magnetic field is compared in 9-10 points.

To catch the feeling of the objective function, the plot of its dependence on just a single parameter (Z) is presented in Fig. 4 One can easily see that the objective function must be multi-modal. Hence the practical implementation of our approach may involve some technical difficulties. For that reason we decided to imply two distinct minimization methods one based on Levenberg-Marquardt [4] algorithm and another using Particle Swarm Optimization [3]. In the first case we use Python bindings to the Levmar library[5], whereas the implementation of the PSO algorithm relies on our own code.

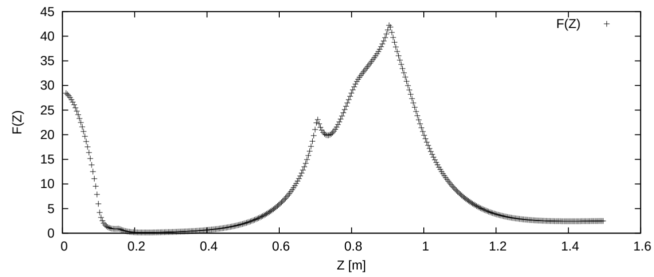

Fig. 4. Objective (1) as afunction of the distance Z between the main coils

IV. Numerical experiments

The suspicion that our objective function can have multiple local optima was confirmed by our first attempts in which the gradient—Levenberg-Marquardt optimizer—was used. We found that this algorithm was rarely capable to find a real minimum even for the simplified situation in which we have fixed all but one parameter. The only exception was when the starting point was close to the minimum and for this case the algorithm was quickly-convergent. Such a behaviour should actually be expected from a gradient type of algorithm.

The Particle Swarm Optimization algorithm was implemented in its classical version [3], however we decided to modify the particle velocity evolution equation by relaxing its dependence on the velocity of the previous step which is multiplied by a factor of 0.5. By try and error method we found that such a modification works better in our application. The results obtained with the PSO are encouraging, however the minimization requires the use of large swarms and high number of iterations. Yet, the PSO algorithm has great parallel potential and thus it offers a chance to overcome this difficulty.

V. Conclusion

A simplified model of the stray field of an MRI scanner may be constructed on the basis of a computationally-effective semi-analytical model of cylindrical coils. To find the proper dimensions of these coils an inverse problem must be solved. Application of gradient method seems to be ineffective in that case, since the problem has several local solutions. An experimentally tuned PSO algorithm seems to be able to find the global solution.

References

[1] Krawczyk Z., Starzyński J. Parallel implementation of exact formulae for magnetic field of axisymmetric current distributions, Przeglad Elektrotechniczny, 11a/2012, ISSN 0033-2097, pp. 56-58

[2] Conway J.T. Trigonometric Integrals for the Magnetic Field of the Coil of Rectangular Crossection, IEEE Transactions on Magnetics 5, 2006, pages 1538-1548, vol. 42

[3] Kennedy J., Eberhart R. Particle swarm optimization, Proceedings of IEEE International Conference on Neural Networks. IV. pp. 1942-1948

[4] Levenberg K. A Method for the Solution of Certain Non-Linear Problems in Least Squares. Quarterly of Applied Mathematics 2/1944 pp. 164-168.

[5] Levmar, `http://www.ics.forth.gr/~lourakis/levmar/`