Limits on Shielding for MRI Coils

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Overview

Shielding is vital to high performance in all components of the magnetic coil system in MRI. As the systems become smaller and more open, demands on the shield coils are increasingly stringent. To meet this challenge, a three-step procedure for evaluating and improving the active shielding of a given coil geometry is presented.

Imperfect Open Shielding

While closed or infinite shields can give perfect screening [1], an open shield (a coil with at least one aperture) has some nonzero level of field leakage. Consider first a two-dimensional problem, such as the cross section of axial currents on long coils. From Maxwell's equations, the two rectangular field components satisfy Cauchy-Riemann conditions away from the sources, and yield the real and imaginary parts of an analytic function. If there were perfect shielding, this function must vanish in some exterior region. However, by analytic continuation to points inside the open coil by paths through the aperture, the magnetic field must vanish everywhere inside as well. This contradicts any nonzero values desired inside, and the contradiction can be extended to three dimensions by the theory of harmonic functions (the magnetic field can be derived in source-free regions from a potential that satisfies Laplace's equation).

Shielding Error: Evaluating, Tuning, and Limiting

The supershielding equations of Ref. [2] can be combined into one equation to define a shielding-error function. Again consider a two-dimensional problem, with a generalization to three dimensions possible for coil geometries of practical interest. Let x be the position along a line separating the shield and source regions. We find

$$\varepsilon(x) = f_2(x)\,\theta(L_2 - |x|) - \int_{L1} \boldsymbol{K}(x,y)\, f_1(y)\, dy \qquad (\mathbf{1})$$

where f_1 (f_2) is the primary (shield) current distribution. The kernel $\boldsymbol{K}$ arises from a transform of the magnetic-field Green function. The finite coil sizes L_i are reflected by the θ function and the integration limit. The shielding-error function $\varepsilon(x)$ is a direct measure of how good the screening is, not only along the line but everywhere in the shield region.

This suggests a shielding design procedure, subject to nonzero field constraints in the DSV region. (I) Evaluate $\varepsilon(x)$ via Eq. (1), and thus the shielding, for a given set of current distributions. (II) Use iteration or other techniques to reduce ε in those regions where improvements in shielding is needed. (III) Determine the behavior of the coil currents that will minimize $\varepsilon(x)$, at least in the mean square sense. To carry this out, (1) can be analyzed as an eigenvalue problem of an integral operator. These steps are carried out for an example in the next section.

An Example

In Ref. [2] a solution for a parallel-strip shielding problem was given. We have studied the corresponding $\varepsilon(x)$ and we have used a new variational approach to improve it to a new shielding function that is everywhere two orders of magnitude smaller. This directly translates into the improved shielding seen in Fig. 1 for strips 0.1m apart. On the question of the best screening available, we are able to prove that the mean square error can be made arbitrarily small for a single nonzero interior constraint [3].

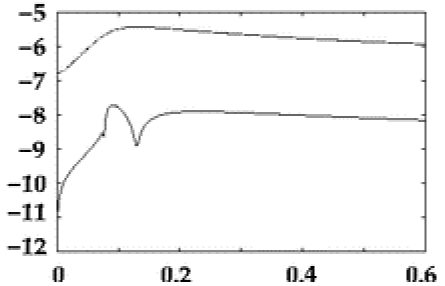

Figure 1: A semi-log plot of the magnetic field 1cm above the shield strip (0.3m wide) and from the center outwards. The top (bottom) curve is the old (new) solution.

Our studies of cylindrical, planar, and disk geometries [4] mirror the success of the evaluating, tuning and limiting steps for the parallel-strip example. Significant improvements on existing solutions can be made and room exists for further significant improvements.

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References

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[3] We have also made numerical studies of the limiting intricate current distributions and the statistical properties of the eigenvalues of the integral operator. This work is also of intrinsic mathematical interest, since, in contrast to the differential operator problem, considerably less is known about the eigenvalues and eigenfunctions of the integral operator.
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