Capping off the actively shielded cylindrical gradient story

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Abstract

Eddy currents produced by the residual field from actively shielded gradients cause the inner bore of the cryostat to vibrate. These vibrations produce acoustic noise and the eddy currents affect image acquisition and processing. We propose a new design for an actively shielded, cylindrical transverse gradient coil with endcaps. The active windings of the shielding coil are extended over the ends of the gradient coil form and inward to its inner radius. The design was accomplished using a 'target-field-like" approach. The peak fringe field reduction with this approach is observed to be approximately 70%.

Introduction

A conventional gradient assembly consists of three primary gradients and three corresponding secondary active shielding coils for suppressing eddy currents on the metallic structure of the MRI system. Realistically, these eddy currents cannot be completely eliminated. The residual eddy currents from all coils create image artifacts and Lorentz forces resulting in high levels of acoustic noise [1]. This problem becomes more acute in high field systems. The SUSHI shielding-function approach [2] can significantly reduce eddy current production. However, SUSHI leads to negative primary currents and a consequent increase in peak current and coil inductance. An active passive shielding combination has also been proposed [1] to address the eddy current issue.

As a continuation of our earlier work on an axial gradient coil design [3], we have studied a shielded transverse-gradient coil assembly with radial, active endcaps at both ends of the coil. An active endcap configuration reduces fringe fields by 70% compared to a traditional gradient coil of the same length and radial dimensions. The eddy currents induced in the inner bore are proportional to the fringe field, so fringe field reduction results in less power dissipated in the structure and less noise.

Theory

Figure 1 depicts the geometry of the proposed gradient structure. The primary and secondary coil radii are R_p and R_s with corresponding lengths $2L_P$ and $2L_s$, respectively. The endcaps have inner radius R_c and outer radius of R_s. The current densities for the primary *P*, shielding *S*, and annular caps *C* have the form

$$\boldsymbol{J}^{(P,S)}(z,\phi) = \sum_n \left(b_n^{(P,S)} \bullet \boldsymbol{f}_n^{(P,S)}(z,\phi) + c_n^{(P,S)} \bullet \boldsymbol{g}_n^{(P,S)}(z,\phi) \right)$$
$$\boldsymbol{J}^{(C)}(r,\phi) = \sum_n \left(d_n^{(C)} \bullet \boldsymbol{h}_n^{(C)}(r,\phi) + e_n^{(C)} \bullet \boldsymbol{k}_n^{(C)}(r,\phi) \right) \qquad [1]$$

where $b_n^{(P,S)}, c_n^{(P,S)}, d_n^{(C)}$, and $e_n^{(C)}$ are the expansion coefficients, and $\boldsymbol{f}_n^{(P,S)}(z,\phi), \boldsymbol{g}_n^{(P,S)}(z,\phi), \boldsymbol{h}_n^{(C)}(r,\phi)$, and $\boldsymbol{k}_n^{(C)}(r,\phi)$ are orthonormal basis functions which are nonzero only inside the assumed length of the primary, secondary and cap structure. A functional is constructed of quadratic terms corresponding to target fields at different constraint points and energy terms of the whole gradient system. The iterative method [4] is used to find the minimum of the functional *W*

$$W = a_1 E + a_2 \sum_{i=1}^{N_{dsv}} \left[B_z(\boldsymbol{r_i}) - B_{z_i} \right]^2 + a_3 \sum_{j=1}^{N_{shield}} \left[\boldsymbol{B}(\boldsymbol{r_j}) \right]^2 \qquad [2]$$

The first term is the total energy of the system. The second corresponds to the target gradient field constraints inside the DSV. The last term includes shielding constraints at the inner cryostat bore. a_1 a_2 and a_3 are weighting parameters that assign relative importance to individual terms. Inside the DSV, a total of N_{dsv} predetermined points at $\boldsymbol{r_i}$ with desired field value B_{z_i} are considered. N_{shield} points at $\boldsymbol{r_j}$ are considered at the cryostat inner bore to reduce field leakage.

An iterative method finds the minima of the functional W through variations in the expansion coefficients in Eq. [1]. Using the law of current conservation the number of independent variables (coefficients) can be reduced. The set of linear equations generated from minimizing W are solved by inverting a matrix that depends on the original coefficients. Each repetition of the iterative method generates a new set of coefficients with increased accuracy.

Results and Discussion

The x-gradient coil is designed with gradient strength of 30 mT/m. The radii for primary and secondary coils are R_P=0.3405m and R_S =0.4411m. Total lengths are $2L_P$ =1.13m and $2L_S$=1.348m. The radial length of the endcap is R_C= 0.06m. A 0.45m DSV is considered. Maximum deviations of 10% linearity and 20% uniformity are allowed within the DSV. Figure 2 shows a discretized quadrant of the primary, secondary and cap coil. Figure 3 compares the fringe field for the continuous solutions for the traditional design and the new design. The field is plotted at the cryostat inner bore radius of 0.475 m and an azimuthal angle ϕ=0. The new design achieves a fringe field of less than 259μT, a 70% reduction with respect to the traditional design.

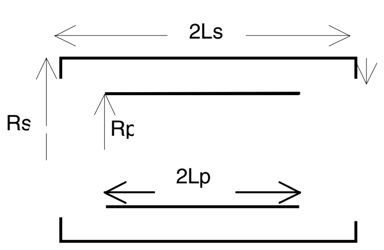

Figure 1

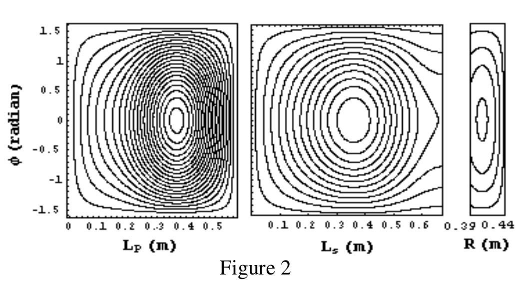

Figure 2

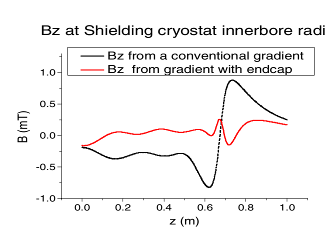

Figure 3

Acknowledgment

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