Shimming Permanent Magnet of MRI Scanner

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Abstract—In this paper an approach of ferromagnetic shimming for permanent MRI magnet is presented. It is designed to reduce unhomogeneity of magnetostatic field of permanent magnet to meet the stringent requirement for MRI applications. An optimal configuration of ferromagnetic pieces is generated through calculation according to the initial field map and the demanded final homogeneity specifications. This approach uses a minimization technique that makes the sum of squared magnetic moment minimum to restrict the amount of the ferromagnetic material used and the maximal thickness of shim pieces stacked at each position on the shimming boards. Simulation results verify that the method is effective and efficient.

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As well known there are two kinds of MRI [1] magnets: closed cylindrical superconductive(SC) magnet and open biplanar-pole permanent magnet such as C-shaped one. The open space of the C-magnet helps the patient overcome any feelings of claustrophobia that may be experienced in a closed designed magnet. Both superconductive and permanent magnet must be shimmed to reduce the unhomogeneity of the magnetic field in the working magnetic field volume to within a predetermined specification, i.e., within a few parts per million for use in medical diagnosis. However, to the permanent magnet due to approximation in the design as well as magnetizing and fabricating tolerances, the final homogeneity of main magnetic field is often far away from the acceptable level. Therefore, shim technology is of major importance in the design and manufacture of permanent MRI magnet. Many papers [2–4] and patents [5, 6] published focus on passive steel shimming of the SC magnet. As for active coil shimming of the SC magnet, likewise there are many papers [7, 8] published. Recently target field method [9–11] has been used for active shimming of SC magnet.

Conventional electromagnetic shimming follows the approach based on representing the field as a spherical harmonics series:

$$B_z(r, \theta, \phi) = \sum_{n=0}^{\infty} \sum_{m=0}^{n} r^n P^m_n (\cos \theta) (A^m_n \cos m\phi + B^m_n \sin m\phi)$$

Amplitudes of harmonic components \((A^m_n, B^m_n)\) are calculated from the magnetic field measured in or around imaging region. To the MRI permanent magnet [12, 13] including spaced-apart first and second pole faces, a common active current shimming technique is the use of biplanar correction coils [14, 15]. These biplanar coils consist of windings placed on parallel planes, and the magnetic field of interest is created in the space between them. These coils are designed to produce corresponding spherical harmonics [7] and have the merit of not interfering with each other. Generally speaking, active current shimming is used for corrections after a patient’s access. Recent progress is that Forbes et al. [16, 17] apply target-field method to design the biplanar shim coils. An alternative is the passive shimming technique [18, 19] using passive ferromagnetic shim configuration to produce different spherical harmonics, the complexity of which increases with harmonic order. In addition, the magnetic moment of a passive iron piece is uni-orientation, its magnitude depends on the strength of the local magnetic field unless saturated, and the passive iron or steel shims have magnetic coupling between them and interfere with each other. Despite the passive ferromagnetic shim approach gives rise to technological difficulties, especially compensating high ordered harmonics, passive shimming is still the preferred method due to its advantages that no power is required and passive ferromagnetic shims are less expensive than active current shimming coils.

Three-dimensional and two dimensional finite element analysis (FEA) techniques have also been used for preliminary mechanical shimming [20]. However, the application of FEA has encountered its bottle-neck because its precision is inadequate to meet the stringent technical demand in MRI.
Though mechanical shimming has the merit that requires no extra power and implementation cost is low, it has generally been empirical.

The aim of this paper is to extend Dorri and Vermilyea’s method [3, 5] from cylindrical SC magnet to biplanar-pole permanent one and substituting passive ferromagnetic shims with active ferromagnetic shims. However, the active ferromagnetic shimming method presented here is a sort of linear mapping that directly links magnetic field to the sources without corresponding to spherical harmonics. The reason why active ferromagnetic material not iron is used in this kind of shimming is because active ferromagnetic shim have invariable magnetic dipole moment.

1. METHOD

Typical permanent magnet with a pair of opposing parallel shimming boards attached to each pole face. Holes containable of shims are evenly positioned on the shimming boards as shown in Fig. 1(a) and Fig. 1(c). These active ferromagnetic shims with magnetization are placed in holes on the shimming boards and the magnetic field of interest is created in the space between them. This construction provides the ease of fabrication and assembly of shims with required thickness. The shimming process begins by measuring the magnetic flux density at all the sampling points over the imaging region, and then the distribution of $\Delta B$, which is the deviation of the flux density from its expected value, obtained by measurement can be achieved. The object of shimming is to find a reasonable placement of active shims on the shimming boards so that $\Delta B$ is eliminated, thereby to better reduce three-dimensional magnetic field unhomogeneity.

In this method the thickness and orientation of the shim pieces on the shimming boards is the design variable to be determined. The magnetic moment of the shim pieces at each position may be positive or negative. Therefore a good algorithm and an optimization computer code are needed.

2. THEORY

According to Maxwell electromagnetic theory, the magnetic induction field generated by a point magnetic dipole is

$$\vec{B} = \frac{\mu_0}{4\pi} \frac{3(\vec{\mu} \cdot \vec{r}) \vec{r} - \vec{\mu} r^2}{r^5}$$

(1)

here $\vec{\mu}$ the magnetic moment of a magnetic dipole and $\mu_0$ the vacuum magnetic permeability. In the case of active ferromagnetic shimming, the ferromagnetic shims are circular or square. The shims piled at each position on the shimming boards can be deemed as magnetic dipoles orientating to $\pm z$-axis while the shimming boards lie at $z' = \pm z_0$ respectively. In practice the shim pieces should be inserted into the predetermined holes of shim boards. We only need to concern the $B_z$-component within the central sphere region generated by these dipoles because $\vec{B}$ field is determined to be homogeneous if one of its three components is homogeneous. Suppose $\vec{r}_i$ represents the coordinate of the $i$th measured field point; $\vec{r}_j$ of the $j$th source point. The magnetic induction field at $\vec{r}_i$ generated by the $j$th shim dipole can be written as

$$B^j_z(\vec{r}_i) = \frac{\mu_0 \mu_j}{4\pi} \frac{2(Z_i - Z'_0)^2 - (X_i - X'_j)^2 - (Y_i - Y'_j)^2}{|\vec{r}_i - \vec{r}_j|^5}$$

(2)

We let $\vec{M}$ express the $m$ dimensional serial of magnetic dipoles, $\vec{B}$ the $n$ dimensional serial of compensation induction field. The linear relationship is expressed as

$$\vec{B} = \vec{A}\vec{M}$$

(3)

Here $\vec{A}$ is the $n \times m$ dimensional transformation matrix. This problem can be solved directly by inversing the matrix $\vec{A}$ if $n$ equals to $m$. However, $\vec{M}$ calculated in this way is distinctly definite and may not be controlled. In order to overcome this difficulty, we developed a method that minimizes the sum of squared magnetic moment. The dimension $m$ should be greater than $n$ in order to give space for confinement.

The confinement can be written in matrix form

$$\text{MINIMIZE } F = \vec{M}^T\vec{M}$$

(4)
Using Lagrange’s method of undetermined multipliers, target function is constructed as

\[ G = \vec{M}^T \vec{M} - 2\vec{\lambda}^T \left( \vec{A} \vec{M} - \vec{B} \right) \]  

(5)

where \( \vec{\lambda} \) representing Lagrange’s multiplier vector. Applying \( \frac{\partial G}{\partial M_i} = 0 \) one can get

\[ \vec{M} = \vec{A}^T \vec{\lambda} \]  

(6)

Inserting vector \( \vec{M} \) into original field equation, one can derive

\[ \vec{B} = \vec{A} \vec{M} = \vec{A} \vec{A}^T \vec{\lambda} \]  

(7)

Here \( \vec{A} \vec{A}^T \) is an \( n \times n \) dimensional squared matrix. Assuming the existence of its inverse matrix, vector \( \vec{\lambda} \) can be determined as

\[ \vec{\lambda} = \left( \vec{A} \vec{A}^T \right)^{-1} \vec{B} \]

(8)

The optimized magnetic dipole moment vector is calculated by the equation

\[ \vec{M} = \vec{A}^T \vec{\lambda} = \vec{A}^T \left( \vec{A} \vec{A}^T \right)^{-1} \vec{B} = \vec{A}_v \vec{B} \]  

(9)

After that the optimal thickness of the \( j \)th dipole consists of shim pieces can be determined if the remanence of the ferromagnetic material is known:

\[ t_j = \frac{\mu_0}{B_r \cdot S} M_j \]  

(10)

here \( B_r \) represents the remanence and \( S \) the sectional area of the shim pieces.

Table 1: Parameters of the Helmholtz system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius of main coils (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>distance between coils (m)</td>
<td>0.5</td>
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<tr>
<td>superconducting current supposed (A)</td>
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</tr>
<tr>
<td>central magnetic field (Gs)</td>
<td>179.8353</td>
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<tr>
<td>radius of shimming boards (m)</td>
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<tr>
<td>distance between up &amp; low boards (m)</td>
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</tr>
<tr>
<td>radius of shim pieces (cm)</td>
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</tr>
<tr>
<td>radius of target imaging region (m)</td>
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<tr>
<td>configuration of sampling</td>
<td>3 × 3 × 3</td>
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<tr>
<td>lattice constant of sampling points (m)</td>
<td>0.08</td>
</tr>
<tr>
<td>number of sampling points</td>
<td>27</td>
</tr>
<tr>
<td>unhomogeneity before shimming (ppm)</td>
<td>1763.498*</td>
</tr>
<tr>
<td>unhomogeneity after shimming (ppm)</td>
<td>117.469*</td>
</tr>
<tr>
<td>total number of shim positions ( m ) (case I)</td>
<td>346</td>
</tr>
<tr>
<td>maximal thickness of shim pieces (mm)</td>
<td>5.1</td>
</tr>
<tr>
<td>total number of shim positions ( m ) (case II)</td>
<td>558</td>
</tr>
<tr>
<td>maximal thickness of shim pieces (mm)</td>
<td>3.6</td>
</tr>
</tbody>
</table>

observed on \( z \)-axis

3. RESULTS

A numerical inspection is presented to test the approach. Consider the quasi-homogeneous magnetic field generated by Helmholtz coil pair instead of the permanent magnet for the sake that its magnetic field can be analytically determined. A series of field points are chosen and the numerical values of magnetic field are used as input to the shimming method. Then the homogeneity of compensated...
Figure 1: Improve the field homogeneity from 1763 ppm to 117 for the larder region; from 235 ppm to 15 ppm for the smaller region. (a) The configuration of the shim pieces positioned on each shimming plate. Notice the total number is 346, (b) The statistical thickness distribution of magnetic dipoles positioned at the two shimming plates. Notice the maximal thickness is 5.1 mm, (c) The configuration of the shim pieces positioned on each shimming plate. Notice the total number is 558, (d) The statistical thickness distribution of magnetic dipoles positioned at the two shimming plates. Notice the maximal thickness is 3.6 mm, (e) Field distribution along x-axis before (dashed) and after (solid) shimming, (f) Field distribution along z-axis before (dashed) and after (solid) shimming.
field is investigated to demonstrate the effectiveness of the method. Table 1 shows geometric parameters, associate parameters of investigated Helmholtz coil system, and corresponding results. Measured field points are chosen as equidistant cubic lattices. For comparison of the dependency relationship of the maximal shim thickness to the number of shimming positions, we investigate two cases. Fig. 1(a) shows the configuration of shim pieces on upper shimming board and that of lower board is identical. Notice that in case I, there are totally 346 positions on the two shimming boards. Among them only 4 positions have the maximal thickness of 5.1 mm. Fig. 1(b) shows the statistics of thickness distribution for those determined dipoles that are used in the shimming and a negative thickness means it is set up inversely. In case II, there are totally 558 positions on the two shimming boards (see Fig. 1(c)) among which only 4 positions have the maximal thickness of 3.6 mm as is shown in Fig. 1(d). In both cases no apex exists at any positions on the two shimming boards, and the field homogeneity is improved over one order of magnitude from 1763 ppm to 117 ppm as is indicated in the last two rows in Table 1. Figs. 1(e) and 1(f) show field distributions before and after shimming for the larger region (20 cm diameter sphere region). Corresponding to the smaller region (13.6 diameter sphere region) where the homogeneity is improved from 235 ppm to 15 ppm.

For the same coil system, same target homogeneity requirement, the maximal shim-thickness will decrease while the number of shim-positions increases (see Table 1 and Fig. 1). Because the gap space between opposing parallel pole faces is expensive, increasing the number of shim-positions on the shimming boards resulting in decreasing the thickness of the shimming boards is of practical significance.

4. CONCLUSION
A complete analytical designing methodology for active ferromagnetic shimming of permanent MRI magnet has been formulated and presented. This approach is adaptive to not only the initial rough shimming procedure but the final refined one too as long as sufficient locations are available in both shimming boards. The simulation results prove that this technique is feasible without a spatial harmonics consideration. Moreover the method is proved to be effective and efficient. It will significantly curtail shimming phase of MRI apparatus. The method presented is currently tryout in MRI magnet manufactory.

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REFERENCES