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# The Optimal Design of Passive Shimming Elements for High Homogeneous Permanent Magnets Utilizing Sensitivity Analysis

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**Abstract** - This paper presents a useful and simple method to design the passive shimming system for homogeneous permanent magnets based on numerical optimization. To simulate the effects of manufacturing and assembling tolerances, the actual geometrical parameter of the magnet with a derivation is suggested. Then, the optimal design model of a passive shim system is set up to correct the derivative of field homogeneity. The numbers, sizes and locations of the passive shims are optimized by the steepest descent algorithm combined with design sensitivity analysis. Two implementations show that the proposed method can achieve the r'equired homogeneity of the field with the minimum quantity of ferromagnetics.

**Keywords**: Optimal design, Passive shimming, Permanent magnet

## 1. Introduction

MRI (Magnetic Resonance Imaging) requires a very high homogeneous static magnetic field. In order to produce high-resolution images, the magnetic field inhomogeneity produced in a high performance MRI scanner must be maintained to the order of several ppm. However, the initial static magnetic field built by virgin magnets is usually less uniform than that required to image successfully because of manufacturing tolerance. Especially with the permanent magnet, the initial inhomogeneity is higher than the order of $10^{-3}$. After manufacturing, the magnet must be adjusted in some points to produce a more uniform field by making small mechanical and/or electrical adjustments to the overall field. This process is known as shimming. The mechanical adjustments, which add small pieces of iron or magnetized materials, are typically called passive shimming, while the electrical adjustments, which use extra exciting currents, are known as active shimming [1]. The active shimming can be easily achieved by adjusting the physical and electrical parameters of the exciting coils. But there are numerous drawbacks associated with it. For example, the electric current in the shim coil may be unstable, which causes "ghosting" in the MR images, and the shim coils are temperature sensitive, which results in image artifacts and furthermore, it is very complicated and expensive. The passive shimming, however, can overcome the disadvantages of the active shimming although it requires numerous iron pieces of which the sizes and locations are concerned with the experience of the designer.

The shimming system can be designed in two ways: analytic and numerical methods. The analytic method uses special-shaped and composed shimming coils or permanent magnetic elements to compensate the harmonic fields of each order. In fact, the harmonic fields above the fifth order can't be compensated by using the analytical method, because it is very difficult to design the higher order shimming [1]. Particularly with permanent magnets, the field error caused by the harmonics of higher orders may be so large that the homogeneity of the field cannot reach a satisfactory uniformity. By using the numerical method, the design directly sets the total field error rather than each harmonic field as the objective of correction. Therefore, it is simpler and more effective than the analytic design method.

In this paper, an intelligent design method of the passive shimming system is presented. The size of shim is determined by using sensitivity analysis combined with the steepest descent method. The proper homogeneity of the magnetic field is also achieved with the minimum quantity of ferromagnetics.

## 2. Description of the proposed method

The proposed method is composed of four steps: 1) acquisition of original magnetic data, 2) expansion of the magnetic field in orthonormal basis set, 3) design of pre-shim or initial shim system, and 4) calibration of shim sensitivity and calculation of shim size needed to get the de-

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sired homogeneity.

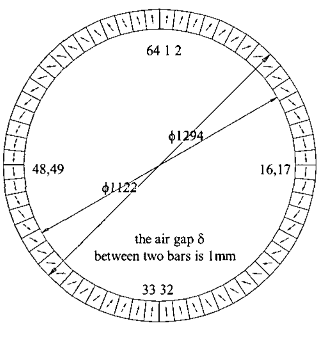
The first step is the preparation of field data for shim design. The basic magnetic field data may be measured for a MRI system. But, in the design stage the measured data may not be available, and therefore, the construction tolerances in manufacturing and assembling are simulated. The field data can be obtained by computing the magnetic field of the magnet under deviation. For example, the permanent magnet system shown in Fig. 1(a) consists of 64 Nd-Fe-B permanent magnet bars in length of 0.8m with the directions of magnetization as follows:

$$\beta_i = (i-1) * 5.625^\circ + 2.8125^\circ \tag{1}$$

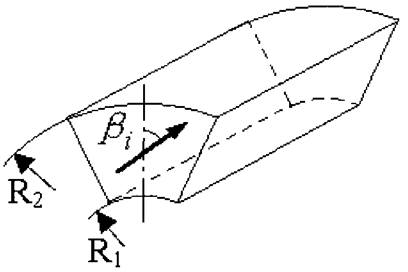
where, $i$ is the number of permanent magnet bar, and $\beta_i$ is the angle from the symmetrical axial of each bar. Fig. 1(b) shows the magnetized direction in a block. To simulate a magnetic field with manufacturing tolerance in the direction of magnetization, the direction of magnetization of each permanent magnet bars with little deviation is assumed as:

$$\beta_i = (i-1) * 5.6^\circ + 2.8125^\circ \tag{2}$$

After computing the magnetic field by using the F.E. method, the initial field data are obtained. The next step is to expand the original magnetic field data in the form of a polynomial expansion having a predetermined number of harmonic terms. It is necessary for two reasons. First, if the original magnetic field is seriously inhomogenous, a special pre-shim should be made by examining the harmonic terms, determining which harmonic term of the polynomial expansion should be modified in order to change the homogeneity. Second, it is helpful for the design of the initial shim system, which is the first step in the optimization process. The initial size and position can be determined by the harmonic analysis result. Supposing the magnetic field of the permanent magnet is along the $z$ direction in a magnetically homogeneous region, the dominant component $B_z$ can be expressed in a spherical harmonics series as follows:



(a) Cross section of the permanent magnet



(b) one of the Nd-Fe-B bars

**Fig. 1.** A test example of the permanent magnet

$$B_z = B_0 + \sum_{n=1}^{\infty}\sum_{m=0}^{n} r^n P_n^m(\cos\theta)(A_n^m \cos m\alpha + B_n^m \sin m\alpha) \tag{3}$$

where, $B_0$ and $(A_n^m, B_n^m)$ are the homogenous magnetic field value and the amplitudes of harmonic components in the volume of interest. Using the magnetic field data, the amplitudes of harmonic series can be best determined by solving the following equation:

$$\text{Minimize } \sum_{i=1}^{N_m} (B_{zi} - \tilde{B}_z)^2 \tag{4}$$

where, $N_m$ is the number of measured points, $B_{zi}$ is the i-th magnetic field value of the known data set, and $\tilde{B}_z$ is assumed to be adequately represented by a finite number of terms of (3).

Based on the dominant terms of the harmonics, we can design the preshim or initial passive shim system. This step is usually for open type MRI magnets because its initial inhomogeneity is higher than $10^{-3}$ order. The preshim is to improve the homogeneity by modifying the shape of the pole piece [2], or by using an iron element having specified physical dimensions, such as rings, arcuate segments and blocks [3]. The initial passive shim system is composed of the shim element having a predetermined size. Each dominant term of the harmonics should be compensated by shim elements with proper location [3].

The next step is the optimal design of a passive shim system by using small magnetized pieces. Our purpose is to design a passive shimming system to compensate the high order of harmonic field and obtain the highest homogeneous magnetic field.

With the pre-shim or initial shim, the inhomogeneity of the initial field may be less than $10^{-3}$, and the shimming elements should be very small. Here we utilize small magnetized pieces, such as magnetic dipole, to improve the field homogeneity. A magnetic dipole located at $(x_s, y_s, z_s)$ will produce a magnetic field at point $(x, y, z)$ as:

$$\mathbf{B}=\frac{\mu_0}{4\pi r^3}\left[\frac{3}{r^2}(\mathbf{M}\cdot\mathbf{r})\mathbf{r}-\mathbf{M}\right] \tag{5}$$

where $\mathbf{M}=V\mathbf{m}$ ; $\mathbf{m}$ is magnetizing intensity in the direction of the main magnetic field, that is $\mathbf{m}=m_z\mathbf{k}$ ; $V$ is the volume of shim piece; $\mathbf{r}=(x_s-x,y_s-y,z_s-z)$ ; $(x_s,y_s,z_s)$ is the coordinates of the located shim. The optimization model is

$$\begin{aligned}&Minimize\ F=\sum_{p=1}^{N}\left(B_p-B_0-\sum_{k=1}^{N_s}B_{p,k}\right)^2+\alpha\sum_{k=1}^{N_s}V_k^{\,2}\\&Subject\ \ 0\le V_k\le V_{\max}\end{aligned} \tag{6}$$

where $k=1,\dots\dots,N_s$ is for shimming blocks, $p=1,\dots\dots,N$ for testing points, $B_p$ is the initial field at each testing point, and the magnetic field $B_{p,k}=A_{p,k}V_k m_z$ produced by shimming pieces is calculated by (5), and $\alpha$ is a weighting factor to dictate the relative minimization of the total volume of shim and field inhomogeneity. For example, $\alpha=0$ indicates that the aim is to minimize the field inhomogeneity and to neglect the total shim volume. For the solution of (6), the gradient search method based on design sensitivity analysis is used. The design sensitivity of the objective function with respect to the design variables can be written as follows:

$$\frac{\partial F}{\partial V_k}=-2\sum_{p=1}^{N}\left(B_P-B_0-\sum_{k=1}^{N_s}B_{p,k}\right)A_{p,k}m_z+2\alpha V_k \tag{7}$$

The new design variables are obtained according to a modified one dimensional line search as follows:

$$[V]_{q+1}=[V]_q+\alpha[s]_q \tag{8}$$

$$[s]_q=-\nabla f_q+\beta_q[s]_{q-1} \tag{8-1}$$

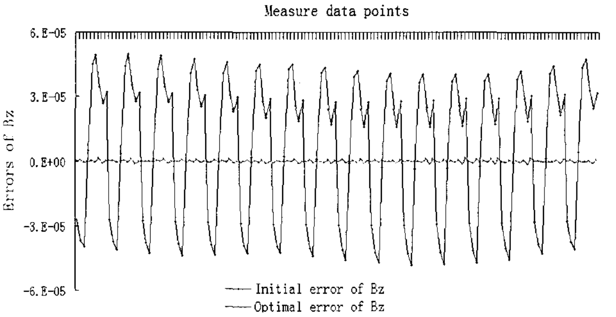
$$\nabla f_q=F(V)\frac{dF}{d[V]}\Big/\left\|\frac{dF}{d[V]}\right\|^2 \tag{8-2}$$

$$\beta_q=\frac{(\nabla f_q-\nabla f_{q-1})^T\cdot\nabla f_q}{\nabla f_{q-1}^{\ T}\cdot[s]_{q-1}} \tag{8-3}$$

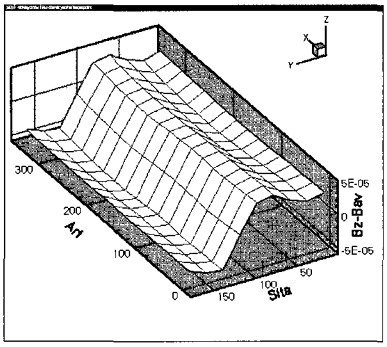
## 3. Numerical application and results

### 3.1 Example 1: Passive shim for a superconducting magnet

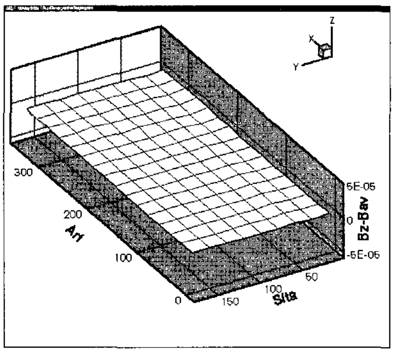
The original magnetic field data comes from a superconducting magnet, which is the first superconductive NMR imaging magnet produced in China [4]. There are two sets of measured data from 50cm DSV surface. The coordinates Arf and Sita in Fig. 2 and Fig. 3 indicate the α and θ angle in the spherical coordinate system, respectively. By using the proposed optimization method, 900 magnetic dipoles are located on a tube like surface with radius of 0.485m and $|z|<0.6m$. For the first set of measured data, the inhomogeneity can be improved from 162.437ppm to 4.172ppm. For the second data set, the initial and optimum inhomogeneities are 98.022ppm and 5.78ppm, respectively.



(a) The error of Bz



(b) initial case

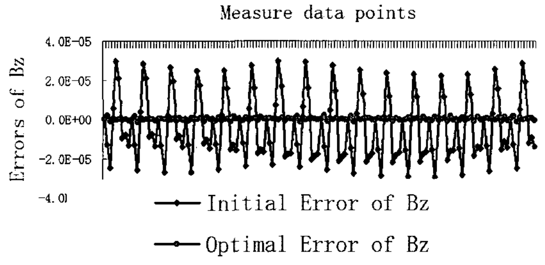


(c) optimal case

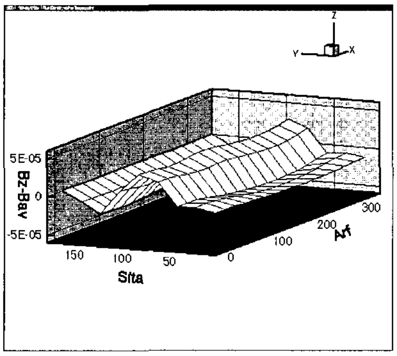
**Fig. 2.** The field error in the initial and optimal case based on the first set of measured data set.

### 3.2 Example 2: Shim design of a permanent magnet with manufacturing tolerance

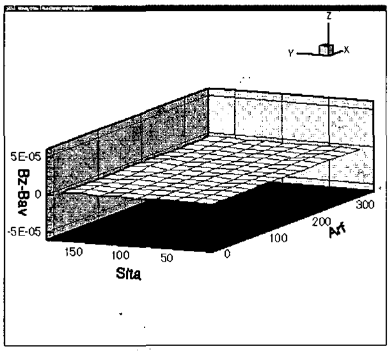
For the permanent magnet geometry shown in Fig. 1, each permanent magnet bar should be magnetized in the direction specified in (1). For the permanent magnet geometry shown in



(a) The error of Bz



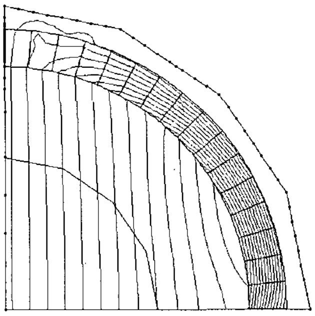
(b) initial case



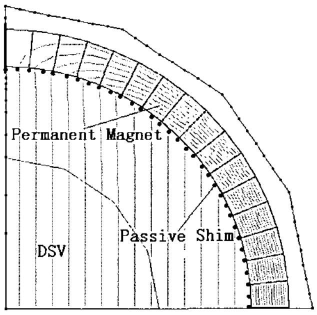
(c) optimal case

**Fig. 3.** The field error in the initial and optimal case based on the second set of measured data

Fig. 1, each permanent magnet bar should be magnetized in the direction specified in (1). However, in the numerical simulation, it is supposed as in (2) to take into account the deviations in manufacturing. The inhomogeneity of the magnetic field is 56649.82 ppm. Fig. 4 shows the magnetic flux distribution. Expanding the original field data in the spherical harmonic form of 2nd order and arranging the pre-shim by using iron rings and bars, the inhomogeneity is increased to 9704.89ppm. Then, 255 test points are arranged in the region of a 0.7m DSV. Passive shims are located on a cylinder with diameter 1.12m and length 0.8m. The position of shims and the interesting region DSV are shown in Fig. 4(b). After the optimal design of the shimming elements, the homogeneity of the field is improved to 256.43ppm. Fig. 5 compares the error distribution of the initial and optimal field. The final flux distribution, presented in Fig. 6, is acceptable.

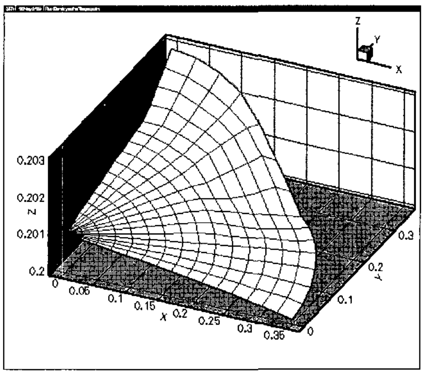


(a) The field distribution of a permanent magnet with some defaults

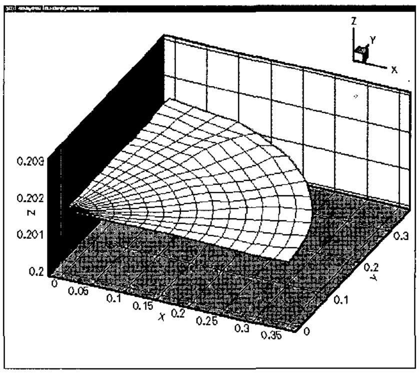


(b) The sketch figure of shims and interesting region

**Fig. 4.** A permanent magnet with some defaults and the sketch figure of shims



(a) after pre-shim



(b) optimal result

**Fig. 5.** The field error distributed in the interesting region

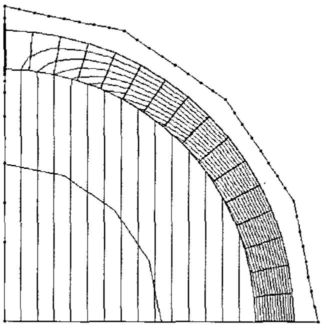


**Fig. 6.** The field distribution after correction with passive shimming

## 4. Conclusions

A passive shim design method is presented in this paper based on numerical optimization. By using sensitivity analysis, the size of shims with the minimum volume of ferromagnetic material can be determined intelligently. The numerical implementations reveal that the proposed method can effectively improve the homogeneity even when the initial fields have different inhomogeneity levels.

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## References

[1] X.H. Jiang, S. Han, "Effect of passive shimming on MRI superconducting and permanent magnets," Proceedings of the International Conference MT-15, 867-869, 1997.

[2] Dong-Hun Kim, et. al., "3D optimal shape design of ferromagnetic pole in MRI magnet of open permanent-magnet type," IEEE Trans. On Applied Superconductivity, vol. 12, No. 1, pp. 1467-1470, 2000.

[3] Pastislav Vadovic, "Magnetic field correction using magnetized shims," IEEE Trans. on Magnetics, vol. 25, No. 4, pp. 3133-3139, July 1989.

[4] X.H. Jiang, S. Han, "Optimization problem in the passive shimming of superconducting NMR imaging magnets," Proceedings of the International Conference ICEF'92, 337-339, 1992.

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