A Hybrid Field-harmonics Approach for Passive Shimming Design in MRI

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Introduction This paper presents a new passive shimming (PS) design scheme for the correction of static magnetic field inhomogeneities in MRI systems. In PS practice, two algorithms are usually used for the determination of an optimal iron piece arrangement. The first technique is a field-based scheme[1,2], which optimizes the PS solution by a minimization of the difference between the targeted field strength and the recorded field over the DSV). This method generally provides good field uniformity but is unable to selectively control contaminant harmonics. The second approach, the harmonics-based method[3], finds the PS solution by a minimization of the difference between the targeted and measured field harmonics and it enables management of targeted impurity harmonics; however high-order harmonics components can be difficult to deal with and the efforts in cancelation of the harmonic components do not always lead to desired overall field uniformity. In this work, we present a new PS algorithm which combines the advantages of the two conventional methods. The PS modelling and optimization procedure has been described and numerical experiments were carried out to illustrate the capability of the proposed method.

Methodology *Spherical harmonic expansion* The PS techniques are developed based on the characterization of the magnetic field where spherical harmonic expansion[3].

$$B_z(r,\theta,\phi)=\sum_{n=0}^{\infty}\sum_{m=0}^{n} r^n P_n^m(\cos\theta)\left[a_n^m\cos(m\phi)+b_n^m\sin(m\phi)\right] \quad (1)$$

Where B_z is the axial field component at the sampling position $F(r,\theta,\phi)$ in the spherical coordinate system; $P_n^m(\cos\theta)$ is the associated Legendre function of order n and degree m; a_n^m, b_n^m are the unknown coefficients in the series expansion. The a_0^0 term is the useful DC harmonic component, all of the other harmonics represent error fields which have to be eliminated.

$$\min\sum_{i=1}^{I}\sum_{j=1}^{J} w_{ij}x(i,j)$$
subject to
$$\begin{cases} -\varepsilon_f \le B_z^s + B_z^r \le \varepsilon_f \\ -\varepsilon_h \le a_{nm}^s + a_{nm}^r \le \varepsilon_h \\ -\varepsilon_h \le b_{nm}^s + b_{nm}^r \le \varepsilon_h \\ 0 \le x(i,j) \le t_{\max} \end{cases} \quad (2)$$

Optimization Problem After spherical harmonic expansion of the measured field, an optimization procedure is then carried out for the prediction of the locations and sizes of ferromagnetic pieces required to correct the field inhomogeneity. For a conventional horizontal system, it can be specified as a mathematical optimization problem as shown in Eq.(2). This mathematical optimization model consists of an objective function and a number of field/harmonic accuracy constraints. Here x is the thickness of iron pieces at location $(z'(i,j),\phi'(i,j)),\ i=1:I,\ j=1:J$, I and J are the allowable numbers of discrete iron pieces in the axial and azimuthal directions, and the shim plate size is generally fixed with a thickness limit: $x\in[0,t_{\max}]$ and configured with defined weighting factors w_{ij}; $\varepsilon_f, \varepsilon_h$ are relaxation factors or allowable peak-peak field or harmonic values. $a_{nm}^r, b_{nm}^r, a_{nm}^s, b_{nm}^s$ are the recorded and shim-piece generated harmonic components, respectively. B_z^r, B_z^s denote the recorded and shimming piece produced field values, respectively. The shim contribution is evaluated in terms of the field value to each field point and spherical harmonic, that is, the $B_z^s, a_{nm}^s, b_{nm}^s$ components are explicitly expressed as $A_f^s x(i,j)$, $A_h^s(a_{nm})x(i,j)$, $A_h^s(a_{nm})x(i,j)$, respectively. The sensitivity matrix A_h^s, A_f^s can be set up based on the evaluation of contribution of small shim arrays to the field points. The unique feature of the hybrid PS algorithm presented herein lies in its explicit constraints of fields/harmonics in the reformulated optimization problem, the solution can be tailored by adjusting the relative weighting of the overall field homogeneity and harmonic components of interest. In this way, one can easily find a practical trade-off solution between fields, harmonics and the weight/configuration of the iron pieces. The PS optimization can be solved by means of a standard convex optimization algorithm.

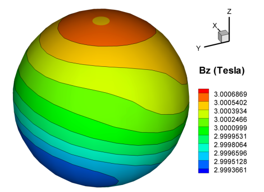

Fig.1. Magnetic field profile over the DSV.

Result In the case study, a 3T magnet system was considered with the DSV size of 40cm and $24(z-)$ X $24(\phi-)$ sampling points were used to evaluate the field quality. The iron plate parameters were as follows: radius-360mm; pockets- $24(z'-)$ X $30(\phi'-)$ pockets; iron piece size-0.27mm. The magnet has initial peak-to-peak field inhomogeneity: 440ppm (see Fig.1), with the presence of both zonal and tesseral harmonics. 576 field sampling points and 16 harmonic components (those with large amplitudes) were considered for the sensitivity matrix constructions. The targets and constraints of the optimization problem are: maximum shim thickness- 12mm; desired field homogeneity- <10ppm; Maximum harmonic amplitude <2ppm. With the help of the hybrid approach, the field homogeneity was brought to a predetermined acceptable level (<10ppm, see Fig.2(a)). In addition, as shown in Fig.2(b), the harmonic components are well controlled, which made subsequent shimming iterations straightforward. The distribution of the shimming pieces is illustrated in Fig.2(c). The total weight and maximum thickness of the iron pieces was 4.6kg and 11.88mm, respectively. For comparison, the harmonics and field based solutions are also provided. Harmonics-approach: the total field errors-about 20ppm, the iron weight is 5.8kg; field approach: peak-to-peak field error-18.8ppm (some of the harmonic components were large (for example, a(7,0)>4.1ppm)), the iron weight is 4.9kg.

Discussion In the given case study, compared with field and harmonics approaches, the hybrid solution requires a minimal amount of iron pieces to offer lowest ppm-value fields over the DSV with tailored individual harmonic impurities. The hybrid approach enables a superior solution giving minimal burden to the next shimming iterations targeting much lower/harmonic field impurities. In addition, the sparse shim pattern produces less eddy current concerns. This method is not only applicable to conventional MRI magnets, but its flexibility means that it also can be easily used to shim unconventional magnets [4].

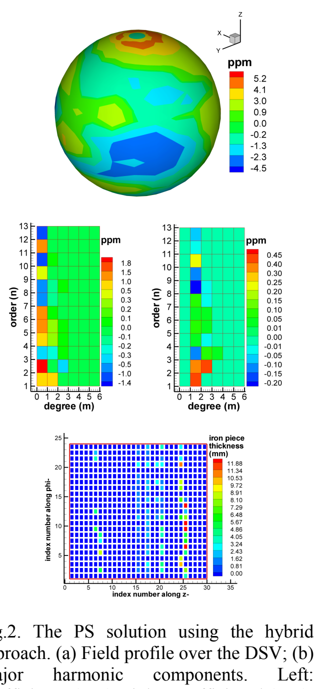

Fig.2. The PS solution using the hybrid approach. (a) Field profile over the DSV; (b) Major harmonic components. Left: coefficient a(n,m); right: coefficient b(n,m). (c) the iron plate profile.

Reference [1] Belov, Bushuev, *IEEE Trans Appl Supercond*, 5, 679-81 (1995). [2] Lopez, Liu, Weber, Crozier, *IEEE Trans Magn*, 44, 394-402 (2008). [3] Romeo, Hoult, *MRM*, 1: 44-65 (1984). [4] Forbes, Crozier, *Med Phys*, 28, 1644-51, (2001).