A new shimming approach using the Equivalent Magnetizing Current (EMC) Method

H. Sanchez Lopez[1], F. Liu[1], A. Trakic[1], E. Weber[1], and S. Crozier[1]

[1]The School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, QLD, Australia

Synopsis: This paper presents a new alternative shimming procedure to correct the magnetic field inhomogeneities generated by horizontal and C-shape biplanar MRI magnets. A magnetization map obtained through the application of the Equivalent Magnetizing Current (EMC) method is used to define the domain where the discrete iron shim set is placed to generate a given field harmonic [1]. Optionally, instead of iron a current pattern is used, then the magnetization is related to the stream function (SF) and the current pattern is placed at equally spaced contours of the SF [1]. If a set of discrete iron pieces with no reversible magnetization direction is employed to mimic the continuous magnetization function (MF) map, then iron shims of unit strength are placed only in the positive domain (valid domain) of the MF map. The field source matrix is calculated only for the discrete elements located in the valid domain, which leads to a better conditioned matrix and superior solutions. An LP algorithm is used to calculate the optimal thickness and location of the discrete ferroshims to produce the target harmonics. Examples of simulated shimming of horizontal/C-shape magnets are presented. In the case of permanent open magnets, the magnetic coupling among the iron pieces and its influence over the magnetic field harmonics is studied for linear and nonlinear iron cases. The influence of the selection and arrangement of individual shim sizes over the field source matrix conditioning is also analysed.

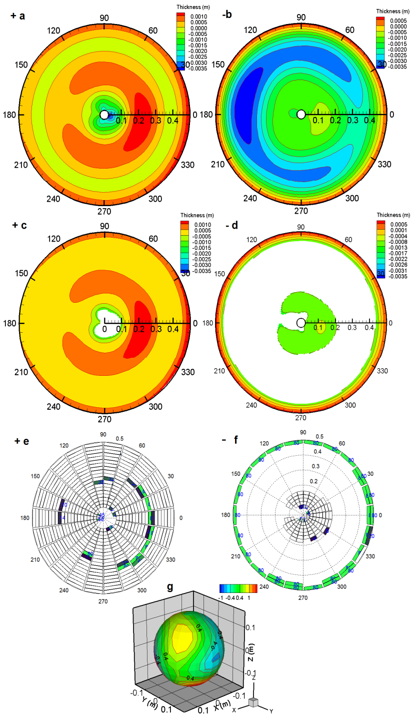
Method: We assume an isotropic, non-hysteresis and homogenous ferromagnetic cylindrical shell of radius R and axial length L, uniformly magnetized ($M_z\boldsymbol{e}_z$) along the axial axis. The cylinder thickness is much smaller than the radius and no magnetization is induced along the radial and azimuthal direction. We consider the shell immersed in a homogeneous magnetizing field $H_c\mathbf{e}_z$ where M_z depends on the position (z',ϕ') and is expressed as a sum of orthogonal functions multiplied by unknown amplitudes ($a_{m'},b_{m'},c_{n'},d_{n'}$):

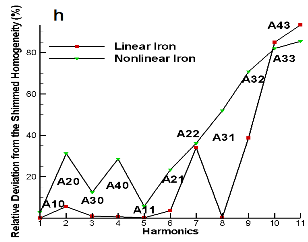
$$M_z(z',\phi')^{\pm}=\sum_{n'=1}^{N}\sum_{m'=0}^{M}h(a_{m'},b_{m'},c_{n'}d_{n'},z',\phi').$$

The parameters N and M define the number of modes along the radial and azimuthal direction, respectively. From the aforementioned assumption and applying the EMC concept, we deduce that $\nabla\times\mathbf{M}=0$ and $\mathbf{J}_m=\mathbf{M}\times\mathbf{e}_r/\mu_0$, and hence $J_\phi(z',\phi')$ is equivalent to $-M_z(z',\phi')/\mu_0$. Using $\mathbf{J}=\nabla\times S\mathbf{e}_r$, it is possible to generate the target harmonic by using a current pattern. In this case, $M_z(z',\phi')$ must be defined such that $\nabla\cdot\mathbf{J}=0$. Expressing the magnetic field generated by the magnetized elements in terms of spherical harmonics and separating the source information from the field spatial dependence, we can write the coefficients corresponding to the magnetic field oscillating harmonics as:

$$A_{nm}=\int_{-\frac{L}{2}}^{\frac{L}{2}}\int_0^{2\pi}C_{nm}(z',\phi')\cos m\phi' dz' d\phi',\; B_{nm}=\int_{-\frac{L}{2}}^{\frac{L}{2}}\int_0^{2\pi}C_{nm}(z',\phi')\sin m\phi' dz' d\phi',$$

where C_{nm} contains the continuous MF $M_z(z',\phi')$. A least squares optimization algorithm is then used to obtain the optimal amplitudes of the MF that minimizes the magnetostatic energy while cancelling the target harmonics and controlling the higher order field components. The resulting continuous magnetization map defines the location of the magnetized iron shims. If no reversible magnetization direction is used and the magnetization is a known variable, then discrete iron pieces with the unit thickness are placed only in the positive domain (valid domain) of the MF map. Using this procedure a better conditioned matrix is obtained and hence superior solutions can be generated. A LP algorithm is applied to obtain the thickness and location of the discrete ferroshims. This process is part of the iterative shimming procedure that finishes when a convergence is obtained. If a current pattern is used, then no iterations are required. For biplanar magnets, we used the EMC method [1] to obtain the map of magnetization-stream function and the valid domain.





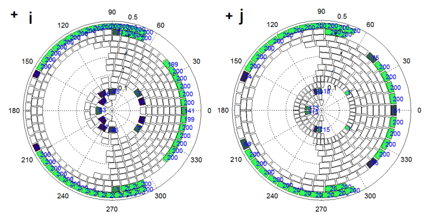
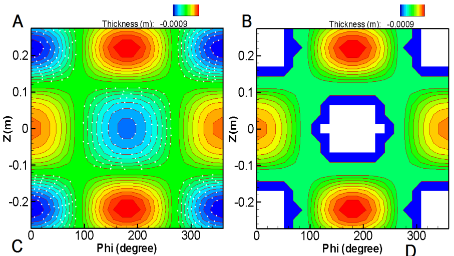
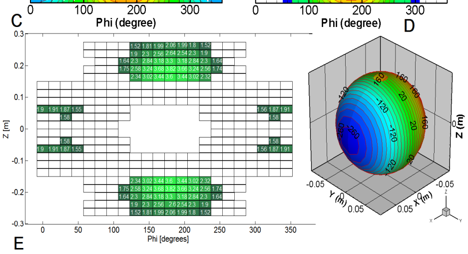


Fig. 2- The continuous MF map (+a,-b) for the pole upper (+) and lower face (-). The valid domain (+c and d) for the discrete shim array (+e and -f). (g) Resulting shimmed magnetic field. (h) Relative deviation of the shimmed inhomogeneity calculated with magnetic coupling in respect to the same parameter that neglects the magnetic coupling. (i,j) The discrete shim array using the same size of the shim pieces (+i) and a variation of design using the different shim sizes (+j).

Results and Discussions: Some examples are shown to illustrate the flexibility of the method. Let us define a target harmonic A_{11}^{target} =-275 ppm. We assume a saturated iron Ms = 2.144 T. The cylinder radius was R=14 cm, L=54.9 cm and DSV =16 cm. Fig. 1-A shows the continuous MF map with negative (dashed) and positive magnetization direction. The discrete shim profile shown in Fig. 1- C was obtained by computing the source matrix (assuming that ferroshims are placed in the valid domain (Fig-1. B)) and applying the LP algorithm. Fig-1. D illustrates the magnetic field generated in the DSV by the discrete shim set. For this computer simulated example no iterations were required. The profile shown in Fig. 1-C generates even zonal harmonics that are three orders of magnitude smaller than the target A_{11}^{target}. The remaining values of the harmonics A_{31}, A_{51} and B_{11} are 500 times smaller than the target. The shim profile obtained by considering the field contribution of all the shims uniformly distributed (conventional technique) requires 1.23 times more iron than the proposed approach. Fig 1-E, shows the equivalent current representation of the magnetization map. The profile is a typical current pattern that produces a gradient along the x axis. The method was also applied for a simulated combination of field harmonics presented at the DSV of a C-shape open magnet. The DSV was 15.5 cm, $Z_0^{\pm}$=46 cm, ρ_{max}=50 cm, ρ_{min}=2.5 cm. A linear and isotropic iron was used for the simulation. The resulting initial inhomogeneity was 447.46 ppm. After applying the presented method, the final simulated homogeneity was 2.87 ppm using 1.29 kg of iron. Using the conventional technique the corrected peak-to-peak field inhomogeneity was 8.79 ppm using 1.4 kg of iron. (See Fig. 2). Fig. 2-h shows the influence of neglecting the magnetic coupling over the shimmed homogeneity when linear or nonlinear iron is used for shimming. The magnetic coupling effect produces a small impact over the low order harmonics and very high impact over high order and degrees when linear iron is used for shimming. When nonlinear iron is used, large errors are generated for low and high orders and degrees. The appropriate selection of the shim size improves the matrix condition and enables superior solutions. The upper face profile shown in Fig. 2-i, uses a uniform shim size to produce a A_{31}^{target} =-275 ppm. The matrix condition number of this design is 397.3 and the target harmonic was produced with an error of 8.13 ppm. The condition number of design (j) was 1.5 times smaller and the error to produce the target was 3.99 ppm.





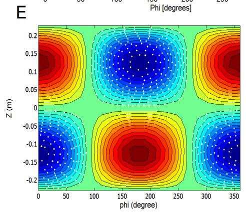


Fig. 1-(A) MF map to produce A_{11}^{target} =-275 ppm. (B) Valid domain. (C,D) Discrete passive shim set and the field profile. (E) The equivalent current pattern.

Conclusions: A new alternative approach for shimming MRI magnets using the EMC method has been presented. The MF map provides useful information about the location and strength of the magnetized pieces. A better conditioned source matrix and hence superior solutions can be obtained by placing the discrete pieces in the valid domain. Using the magnetized dipole as field kernel, the proposed method produces a versatile solution where optionally iron and/or current can be placed to mimic the MF map. In the case of C-open MRI magnets (low field, no saturated iron), neglecting the magnetic coupling produces large errors in higher order harmonics.

References: [1] H. Sanchez, *et al.*, ISMRM 2008, submitted.

Acknowledgements: Financial support from the Australian Research Council is gratefully acknowledged.