Distortion of Gradient Coils Performances in Presence of Iron

A. Borceto[1], A. Viale[1], F. Bertora[1], L. Bertora[2], and R. Bowtell[3]
[1]Robotics,Brain and Cognitive Science, Italian Institute of Technology, Genoa, GE, Italy, [2]Paramed Medical system, Genoa, (GE), Italy, [3]Sir Peter Mansfield Magnetic Resonance Center, University of Nottingham, Nottingham, United Kingdom

Introduction

MRI magnets comprising iron yokes are quite common particularly in low field scanners (<0.3 T). The most important characteristic of these systems is their compactness. Most of these system use unshielded gradient coils, which is economically justified by a reduction of costs and installation space. The presence of high permeability material in these scanners heavily affects the field produced by the gradient coils. The static interaction between the iron pole and the gradient system causes inhomogeneities of the linear field generated in the region of interest (ROI) for imaging, thus causing geometric image distortion [1]. It is therefore important to model the effects of the iron on the coil performances in the design of such gradient systems.
Here we compare three different techniques for modelling the effects of the iron. The performances of the same set of coils have been assessed by modelling the effect of iron using: (i) the method of images [2], (ii) a variant of the boundary element method [3], (iii) commercial finite element software (Opera by Vector Fields Software®).

Method

A transverse, x-gradient coil has been designed using the IBEM method [4] and an iron yoke (600 mm magnet gap) was then added to the system along the same direction as shown in Figure 1. The distance between the coils and the yoke is 48 mm.
The first technique chosen to study the change in the performances of the gradient coil in the presence of the iron is the well known method of images [1]. In this technique the iron is modelled as an infinite flat surface with infinite permeability. The field in the target region is computed as if an identical set of coils, corresponding to the image of the gradient coils (i.e. "mirror coils"), were present at the same distance from the iron as the actual coils. Only the first reflection of the coils has been considered, as the second occurs at an order of magnitude greater distance.
The boundary element method models the iron through the use of the scalar magnetic potential, bounded to be constant on the surface of the iron. This allows the polarization of the iron generated by the coil system to be calculated, and thus the contribution of the iron to the field in the ROI. The iron is still modelled as a linear system, but with the advantage of considering the real geometry of the iron yoke.
In the Opera Vector Fields® software the contribution of the iron is calculated according to the magnetization curve (B-H) of the chosen ferromagnetic material, thus the effect of the B_0 field on the iron is also accounted for.

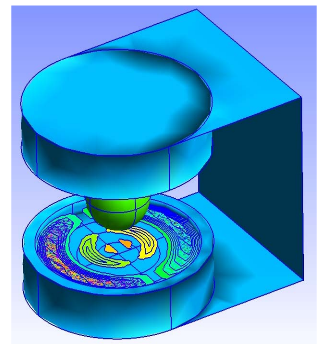

Figure 1: The gradient coils and the iron yoke surface used in BEM computations.

Results

Table 1 lists the coil performances [5] computed using the three different methods along with the time needed for the calculations in each method. The coil in air can be considered a good reference in the comparison, considering that the maximum image distortion it yields is of the same order of magnitude as that produced by the presence of the concomitant fields. The efficiency values are normalized with respect to the efficiency of the coil in air. Figure 2 shows the non-linearity along the x-axis and the non uniformity along the z-axis. The non-linearity, computed with Opera® (red line in Figure 2(a)), is slightly asymmetric with respect to the x = 0 axis, because the software takes into account the saturation of the yoke.

400 mm DSV	AIR	MIRROR	BEM	Opera®
Efficiency	1	1.7	1.65	1.74
Max. Non-Linearity	1.4%	9.3%	17.0%	12.3%
Max. Non-Uniformity	3.5%	4.4%	14.1%	7.7%
Max. Image Distortion xy plane [mm]	0.6	4.8	10.1	6.8
Max. Image Distortion xz [mm]	2.8	4.8	11.1	6.8
Calculation time	~30 "	~1'	~15 '	~10 h

Table 1: Results from the three different methods

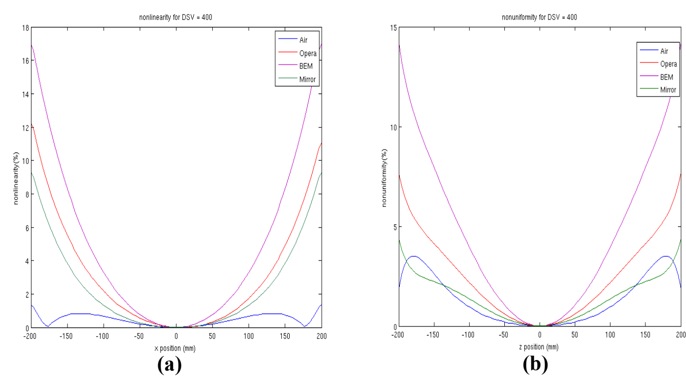

Figure 2: (a) Non-Linearity, ***(b)*** Non-Uniformity

Conclusion

The coil performance calculated using all three methods is highly affected by the presence of the iron. The methods described here can be applied not only for gradient systems, but also for shim coils. Among the three techniques, the Boundary Element Methods offers the best compromise between accuracy and calculation time, taking into account that in this method the saturation of iron is not considered and the permeability is set as infinite. In future all three methods will be incorporated in the IBEM code in order to take into account the effect of iron in the design of gradients.

Acknowledgements

The authors wish to thank Dr. Fabbricatore of the Genoa section of INFN for his help and suggestions.

References

[1] M. Sekihara, M. Kuroda, H. Kohno, "Image restoration from non-uniform magnetic field influence for direct Fourier NMR imaging ", Phys. Med. Biol, Vol. 29 N. 1, 15-24, 1984
[2] P. Hammond, "Electric and Magnetic Images", The Institution of Electrical Engineers, Monograph N. 379, 306-313, 1960
[3] M. G. Abele, H. Rusinek, "Method For Determination Of Optimum Fields Of Permanent Magnet Structures With Linear Magnetic Characteristic", US Patent 5,285,393
[4] M. Poole, R. Bowtell, "Novel Gradient Coils Designed Using a Boundary Element Method", Concepts in Magnetic Resonance Part B (Magnetic Resonance Engineering), Vol. 31B(3), 162-175,2007
[5] Sh. Shvartsman, M. Morich, G. Deemster, Z. Hai, "Ultrashort Shielded Gradient Coil Design with 3D Geometry", Concepts in Magnetic Resonance imaging Part B (Magnetic Resonance Engineering), Vol. 26 B (1), 1-15, 2005