Shimming a 0.2 T Permanent Imaging Magnet with Small NdFeB Magnets

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Introduction

With the advent of powerful, new permanent-magnet materials, the prospect of manufacturing an inexpensive low-field imaging system for less-developed countries is seductive. However, to obtain the initial field homogeneity that permits easy shimming, care must be taken in standardising the mass, dimensions, magnetisation and packing of the NdFeB blocks used in the magnet. These demands increase the cost. We therefore investigated dispensing with such standardisation, and shimming "four-poster" magnets that use "off-the-shelf" blocks and simple construction techniques. This would transfer costs from manufacturing to one-time research. The magnet shown in Fig. 1 has laminated steel pole pieces that hold planar gradient coils, steel Rose rings and a nominal field of 0.2 T. Our homogeneity goal was 20 ppm peak-to-peak over a 30 cm-diameter sphere; an initial estimate of inhomogeneity was 950 ppm with spherical harmonics up to sixth order – 48 terms in all.

Challenges

Steel passive shimming could not cope with this large inhomogeneity as steel magnetisation is uni-directional and massive amounts outside the magnet were therefore needed. Electrical shimming required large currents with much resultant heat. Passive shimming with permanent small magnets on the pole faces was therefore appealing[1,2]. However, 100 small (8 mm diameter, 5mm height) nominally-equal NdFeB shimming magnets (Roco Magnetics Co., Shanghai, China) had a magnetic moment variance > 1%, implying limited reproducibility. In their favour, the magnets stick to the pole faces both aligned with, and opposed to, the main field. However, they magnetise the pole faces locally in an unknown manner that changes with reversal of orientation This symmetry breakage renders problematic the use of linear algebra to compute shimming magnet placement even if pole face magnetisation can be calibrated. A further difficulty is that shimming magnets placed close to the pole face centres are efficient but can introduce higher orders (e.g. eighth). Their zonal field varies approximately as $T_{n0} \propto (n+2)(n+1)(r^{n}/f^{n+3})$, where r is active volume radius (150 mm), f is the distance from the origin to the shimming magnet and n is order. At the pole centres, f is its minimum of 275 mm and the field function T_{n0} converges too slowly as n increases. Finally, without fine temperature control (< 0.1 C) and/or a field/frequency lock, the field drifts, though too slowly to affect images. However, during the 13-plane spherical field plot needed to characterise the inhomogeneity, the drift is tens of ppm which seriously degrades the field analysis.

Methods

Field drift: The problem was solved by recording the time at which each field measurement $B(t)$ was made. The magnetic field was plotted in the usual manner with the aid of a "Metrolab" teslameter (Metrolab Instruments SA, Geneva, Switzerland), one plane at a time, each plane at 25 equally-spaced azimuthal positions (includes 0^o and 360^o azimuths) on the surface of a sphere of radius 150 mm. An axial field plot from -160 to + 160 mm was also taken. However, before each planar plot, and also at the completion of plotting, the field value $B_0(t)$ *at the origin* was also recorded. All times and field strengths were automatically recorded on a laptop computer spreadsheet with the aid of a small interfacing program. The drift $B_0(t)$ at the origin was then fitted to third order and the origin field at the times of the field plot measurements obtained by interpolation. Subtraction of these origin field values from the corresponding planar field plot readings gave, to first order, a drift-free field plot. There was an underlying assumption that the drift in inhomogeneity was negligible. To the order of a few ppm, this was later found to be true. Axial and spherical field plots were conjointly analysed in a spherical harmonic basis set, and to obtain a good fit to the data all orders and degrees up to sixth were needed.

Magnet calibration: Assume that the local magnetisation of a pole face (not at the edges) by a small, attached, circular shimming magnet is cylindrically symmetric. Then further assume that the field created in the active volume can be considered to originate from numerous, small magnetic moments stacked in a line perpendicular to the pole face and passing through the middle of the shimming magnet. To test this hypothesis, 81 positive (aligned) magnets were placed in a square lattice of side 9 cm on a pole face and the field change (~ 3000 ppm) plotted and analysed in spherical harmonics. An array **A** of amplitudes resulted. The matrix equation $\mathbf{A} = \mathbf{M}.\mathbf{L}^{+}$ was constructed linking these amplitudes with an array $\mathbf{L}^{+}$ of 32 unknown, evenly-spaced, line moments running from z = –2m to +2m with no moments between the pole faces. The theoretical expression[1] for the spherical harmonic amplitudes created by a unit magnetic dipole in the z direction at each position was used to calculate the matrix coefficients. Matrix inversion was accomplished by singular value decomposition. Only 7 singular values were needed to give an excellent (~ 5 ppm in 3000 ppm) fit to the data and a calibration $\mathbf{L}^{+}$ for a positive magnet on a pole face was gained. For negative (anti-aligned) magnets, the result $\mathbf{L}^{-}$ was significantly (~10%) different.

Magnet distribution: A 10 mm Cartesian grid was imposed on each pole face, gradient coil supports being avoided. Circular exclusion zones (of variable radius) were imposed around the pole face centres to ameliorate the convergence problem. To allow for iteration, shimming magnets were putatively placed at every other grid point; i.e. on a 20 mm lattice. Using the calibration, a 48 x 3288 matrix equation was then constructed linking spherical harmonic amplitudes to *positive* magnet moment size at each grid position. A second equation linking amplitudes with the *magnitudes* of negative magnetic moments *at the same positions* was then made – the minus signs were included in the matrix coefficients. The two matrices were then combined by doubling matrix width and moment array length. This allows positive and negative magnets at the same site! Matrix inversion by constrained linear programming was then effected whereby the maximum allowable moment was forced to the minimum possible while still having successful matrix inversion. Duplicate populating of a magnet site only occurred when inversion was close to failure. The constraint forces a large number N of magnets at the same, small maximum size to be used, with a remainder of 48 magnets of variable size. The more N >> 48, the less the variable-size magnets matter – they are rounded to zero or the maximum size – and the more the variability of the magnets is averaged.

Software: Apart from the small laptop program mentioned above, all programming and calculations were performed in *Mathematica* (Wolfram Research Inc. Champaign, IL, USA). The various sections were in separate, fully-documented "Notebooks" comprising initialisation, data importation, field analysis, magnet calibration, pole face grid generation, magnet placement and error analysis. With all field plotting data available, the time taken to perform a single pass at shimming varied from 2 to 5 hours, depending on the linear programming constraints and the experience of the operator.

Results

The magnet was borderline shimmable due to a large (340 ppm) z^2 term. This was therefore reduced by adjusting the Rose ring heights and adding large *radial* shimming magnets round their periphery. This permitted a smaller central exclusion zone to be used and at the first pass, a homogeneity of only 49 ppm peak-to-peak was obtained. Residual inhomogeneity was low order, due to variability and magnet rounding, and small high orders caused by convergence issues. The field was brought into specification with additional magnets by inspection. In conclusion, permanent magnets placed on pole faces permit rapidly-convergent spherical-harmonic-basis-set shimming once accurate magnet calibration has been made. Calibration may be effected by the realisation that circularly symmetric pole face magnetisation may be modelled with a perpendicular line of magnetic moments – the key message of this work.

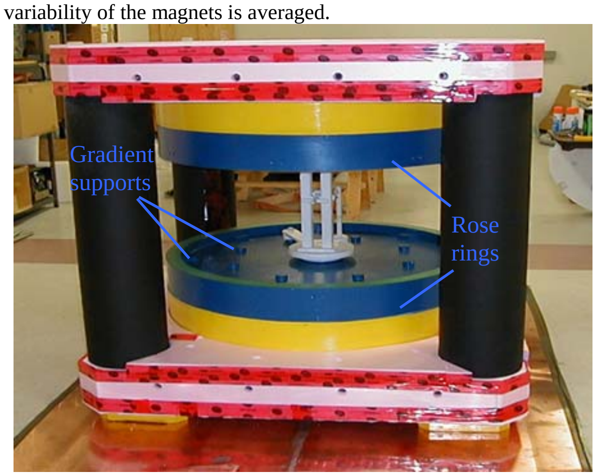

Figure 1. A simple 10 tonne 0.2 T permanent imaging magnet (AMAG, Poland) with field plotting rig. Pole face gap 550 mm, diameter 1.06 m. Outer dimensions 1.42 x 1.42 x 1.31 m.

References

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2. D-H. Kim , J.K. Sykulski and D.A. Lowther, IEEE Trans. Magnetics, **41** 1752, 2005.