Shoulder-Slotted Insertable Gradient and Shim Coil Set

M. Poole[1], D. Green[2], and R. Bowtell[1]

[1]Sir Peter Mansfield Magnetic Resonance Centre, University of Nottingham, Nottigham, Notts., United Kingdom, [2]Magnex Scientific Ltd., Yarnton, Oxon., United Kingdom

Introduction The inverse boundary element method (IBEM) has been shown to be a highly effective approach for the design of gradient and shim coils with geometries and magnetic field requirements of low symmetry [1]. The IBEM approach has been employed here to design an insertable 3-axis head gradient set with sections removed to accommodate the shoulders of subjects, which has subsequently been constructed and tested in imaging experiments at 3 T. This coil set also contains a shielded Z0 shim coil and a full set of 2nd order shim coils within 3 cm of radial space. These coils were designed to have low self-inductance and high efficiency to allow the rapid switching of shim fields required for dynamic shimming [2].

Methods The IBEM models arbitrary surfaces as an ensemble of triangular elements, through which different currents flow in order to generate a prescribed magnetic field in specified regions of interest. The coil system was described in terms of the values of the stream-function of the current density at the corner nodes of the triangular elements, Ψ_n, The axial magnetic field, $B_z(\mathbf{r})$, at a series of points spanning the target region of uniformity (ROU), the inductance, L, resistance, R, and torque vector, $\mathbf{M}$, were all parameterised in terms of Ψ_n and then combined into a functional which was minimised so as to identify the optimal stream function. This stream-function was then regularly contoured to produce the wire paths of the final coil design. The magnetic field due to the coil was calculated by integrating the elemental Biot-Savart expression over the wirepaths and FastHenry© (a rapid impedance calculation programme [3]) was used to calculate the coils' inductance and resistance values. The various coils were wound on concentric cylindrical surfaces with diameters lying between 390 and 450 mm and rectangular sections of each surface were removed to accommodate the shoulders of the subject. All coils were designed to have a ROU which is a central 160 mm diameter spherical volume (DSV). The coils were constructed from water-jet cut copper tracks and set in resin for rigidity. Along with values of R and L, $B_z(\mathbf{r})$ was measured over the 160 mm DSV using a fluxgate magnetometer. The coil set was subsequently tested in the Nottingham-built 3T scanner. Echo planar images (EPI) were acquired with a 40 ms echo-time and 3 mm isotropic resolution. The gradient strengths were measured by scanning a spherical phantom of known size, and maps of $B_z(\mathbf{r})$ produced by the shim coils were measured with an EPI-based field mapping protocol, which involved measuring the phase changes produced when each shim coil was pulsed on for 40 ms between the RF excitation and EPI echo-train.

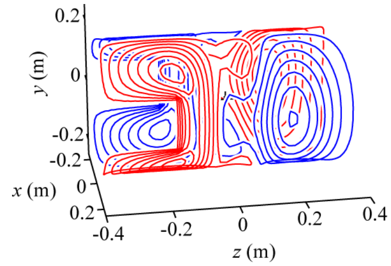

Figure 1. Wire paths of the X-gradient coil where red wires have a reversed sense of current flow with respect to the blue wires.

Figure 2. The completed gradient and shim coil set.

Results As an example of the coil winding patterns, Fig. 1 shows the wire paths of the X-gradient coil. Figure 2 is a photograph of the completed coil set, which shows the position of the shoulder slots. Measurements of the shim coil fields made using the magnetometer showed that the largest spherical harmonic impurity was always less than 10 ppm (of a 1T uniform field), and that the orthogonality of the X- and Y-gradients was accurate to 0.3°. Table 1 summarises a number of the coils' properties, and indicates very good agreement between measured and calculated values Figure 3 shows axial, coronal and sagittal slices from EPI data acquired from a human subject at 3 T using the coil set. Figures 4 a) & b) show maps of the field generated per unit current over a central slice of the 160 mm DSV by the Z2 and ZX shim coils. Figures 4 c) & d) show maps calculated from pure Z2 and ZX spherical harmonics whose amplitudes were set by fitting to the measured field maps. The strong similarity of measured and calculated maps confirms the high homogeneity of the shim coils.

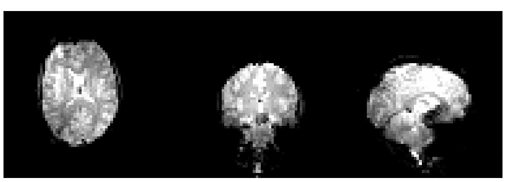

Figure 3. 3 mm isotropic EPI images of a head obtained with the shoulder-slotted insert gradient coil set in a) axial, b) coronal and c) sagittal planes.

Conclusions The IBEM was successfully employed in the design of low-inductance, insertable head gradient and shim coils. The measured efficiencies and inductances of the constructed coils were shown to be in good agreement with the theoretical results obtained from Biot-Savart integration and using FastHenry©. The shim coil inductances are all less than 110 μH thus allowing rapid coil current changes with relatively low shim power supply voltages, as required for dynamic shimming. The uniformities of the gradient and shim coils are all within 5% of the maximum value of the field within the 160 mm DSV.

References **[1]** M. Poole and R. Bowtell, *Concepts in MR: B*, **31**, 162-175 (2007). **[2]** A. Blamire, D. Rothman and T Nixon. *Magn. Reson. Med.*, **36**, 159-165 (1996). **[3]** M. Kamon, M Tsuk and J White, *IEEE T. Microwave Theory & Techniques*, **42**, 1750-1758 (1994).

Acknowledgements We wish to thank Magnex Scientific Ltd. (Now part of Varian Inc., Yarnton, Oxon., UK) for their support of this project.

Property	Coil								
	Z0	X	Y	Z	Z2	ZX	ZY	X2-Y2	XY
a (m)	0.1988	0.205	0.208	0.211	0.2158	0.2165	0.2172	0.2144	0.2151
N	10	7	7	7	6	7	7	9	9
η (μTm^{-n}A^{-1})	9.7 (9.4)	101 (100)	121 (119)	122 (121)	358 (358)	373 (361)	415 (411)	183 (181)	253 (252)
L (μH)	54.6 (36.9)	57.9 (63.7)	52.7 (54.9)	43.8 (53.1)	29.8 (44.7)	64.5 (57.0)	64.4 (69.0)	70.7 (86.8)	98.6 (108.6)
R (mΩ)	115	80	69	51	53	90	85	98	109
Δw_{min} (mm)	5.3	3.7	5.3	7.8	7.0	4.2	7.9	5.8	3.4
η^2/L (T^{2}m^{-2n}A^{-2}H^{-1})	2.5×10^{-6} (2.4×10^{-6})	1.7×10^{-4} (1.8×10^{-6})	2.3×10^{-4} (1.8×10^{-6})	2.8×10^{-4} (1.8×10^{-6})	3.9×10^{-3} (1.8×10^{-6})	2.0×10^{-3} (1.8×10^{-6})	2.2×10^{-3} (1.8×10^{-6})	4.0×10^{-4} (1.8×10^{-6})	5.9×10^{-4} (1.8×10^{-6})

Table 1. Properties of the shoulder slotted gradient and shim coils, including the radius, a, number of stream-function contour levels, N, efficiency, η, inductance, L, resistance, R, minimum spacing between wires, Δw_{min} and figure-of-merit, η^2/L. Values in brackets are calculated values.

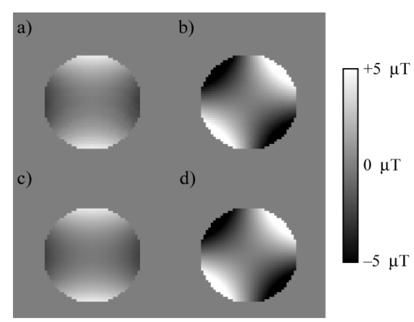

Figure 4. Measured maps of the magnetic field generated per unit current in the y=0 plane by the a) Z2 and b) ZX shim coils. c) and d) show the pure spherical harmonic plots for comparison.