An Insertable, Shoulder-Slotted Gradient and Shim Set for Dynamic Shimming

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Introduction

Magnetic susceptibility induced field distortions may cause signal-loss and geometric distortions in MRI, particularly in EPI. Dynamic shimming [1] aims to ameliorate magnetic field distortions for each slice of a multi-slice acquisition. The efficacy of field homogenisation is greater than conventional shimming of the whole volume, but implementing dynamic shimming requires shim coils of high strength and low inductance to achieve the necessary field switching times. Here we present an insertable set of gradient and shim coils with low inductance and high efficiency designed for use in dynamic shimming with an arbitrary-surface, boundary element method (BEM) [2]. This method of design was used because the coils were to have diameters falling between 380 and 470 mm, and therefore required cut-outs to accommodate subjects' shoulders. Half size versions of the Z2 and ZX coils have been built and tested and a full-size shim set is currently under construction.

Methods

A method where the conducting surface on which the coils are wound is discretised into triangular elements [2] was used to design coils with the geometry shown in Fig. 1. Thsi geometry is a 800 mm long cylinder with a diameter that is different for each coil. Table 1 lists the coils that make up the shim set in radial order. The order and degree of the associated spherical harmonic is given alongside the radius that the coil is designed at and the cartesian form of the spherical harmonic used as the function for the target field. Z0 (P) and (S) are the primary and shield coils of the Z0 shim respectively. The shoulder slots are 220 mm long and are 150 mm wide. In Fig. 1 half of the discretised surface is shown in blue, and has a total of 5456 triangular elements. The region of uniformity is a 160 mm diameter spherical volume containing 93 target field points. The set consists of X, Y, Z gradients and all 2nd order shim coils as well as a shielded Z0 coil. The Z0 coil was designed on a 320 mm long cylinder with a method that expresses the current density as a weighted set of sinusoidal harmonics [3]. The BEM method allows the optimisation of the RMS field error, inductance and resistance whilst imposing torque-balancing. The field generated by the coil was modelled by applying the Biot-Savart law to the wire-paths, and the inductances and resistances were estimated using FastHenry© [4], a multipole impedance calculation. The electromagnetic properties of the coils will be tested when the construction is complete.

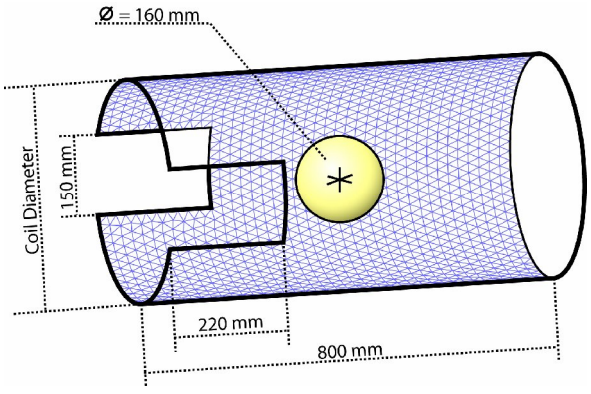

Figure 1. *The geometry of the coils.*

Results

Wire-paths of the X gradient and Z2 shim coils are shown in Fig. 2. The red wires on the X gradient indicate reversed current flow with respect to the blue wires. The current direction for the Z2 shim is shown by arrows. The efficiency, inductance, resistance, and figure of merit (FOM) η^2/L of all the coils are shown in Table 2. Inductances and resistances were modelled with 3 mm diameter wire using FastHenry©.

Coil	Order *n*	Degree *m*	Radius (cm)	Equation of Target Field
Z0 (P)	0	0	19.520	1
X	1	1	20.510	x
Y	1	-1	20.810	y
Z	1	0	21.110	z
X2-Y2	2	2	21.445	$3\,(x^2 - y^2)$
XY	2	-2	21.515	6 xy
Z2	2	0	21.585	$z^2 - {}^1/_2\,(x^2 + y^2)$
ZX	2	1	21.655	3 zx
ZY	2	-1	21.725	3 zy
Z0 (S)	0	0	21.795	0

Table 1. *A list of the coils that make up the shim set.*

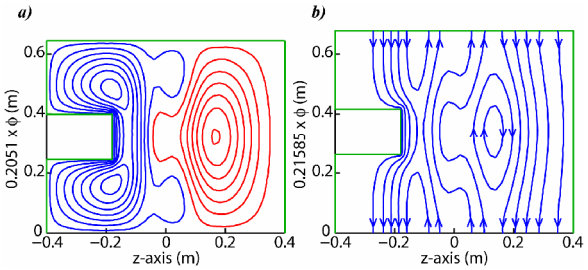

Figure 2. *Wire paths for half of the* ***a)*** *X gradient and* ***b)*** *Z2 shim coils.*

Coil	Efficiency, η ($\mu Tm^{-n}A^{-1}$)	Inductance, L (μH)	Resistance, R (mΩ)	FOM, η^2/L ($T^2m^{-2n}A^{-2}H^{-1}$)	Wire gap (mm)
Z0	9.07	29.0	100.4	2.84×10^{-6}	4.7
Z	120	49.6	50.9	2.90×10^{-4}	5.0
X	90	62.2	80.1	1.30×10^{-4}	5.1
Y	120	62.9	68.9	2.29×10^{-4}	9.5
Z2	340	31.5	52.7	3.67×10^{-3}	5.0
ZX	370	65.4	57.0	2.09×10^{-3}	7.3
ZY	410	75.0	83.9	2.24×10^{-3}	8.3
X2-Y2	180	84.0	97.5	3.86×10^{-4}	5.0
XY	250	112.0	109.0	5.58×10^{-4}	5.0

Table 2. *The efficiency, inductance, resistance, figure of merit, and the minimum gap between wires for all the gradient and shim coils.*

Conclusion

An insertable gradient and shim set with shoulder slots containing all coils up to 2nd order has been designed using a boundary element method [2]. These coils have high efficiency, low inductance, low resistance, and are torque-balanced. The full-size set is currently in production and our ultimate aim is to implement dynamic shimming [1] at 3T and 7T with it.

References

[1] A. M. Blamire, D. L. Rothman, T. Nixon. *Magn. Reson. Med.* **36**, 159-65 (1996). **[2]** R. A. Lemdiasov, R. Ludwig. *Concepts Magn. Reson. B.* **26B**, 67-80 (2005). **[3]** M. Poole, R. Bowtell. *BCISMRM*, 2005, p. 3. **[4]** M. Kamon, M. J. Tsuk, J. K. White. *IEEE Trans. on MTT*. **42**, 1750-1758 (1994).

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