Torque-Figure of Merit Trade-off in Multi-Layer Asymmetric Gradient Coils

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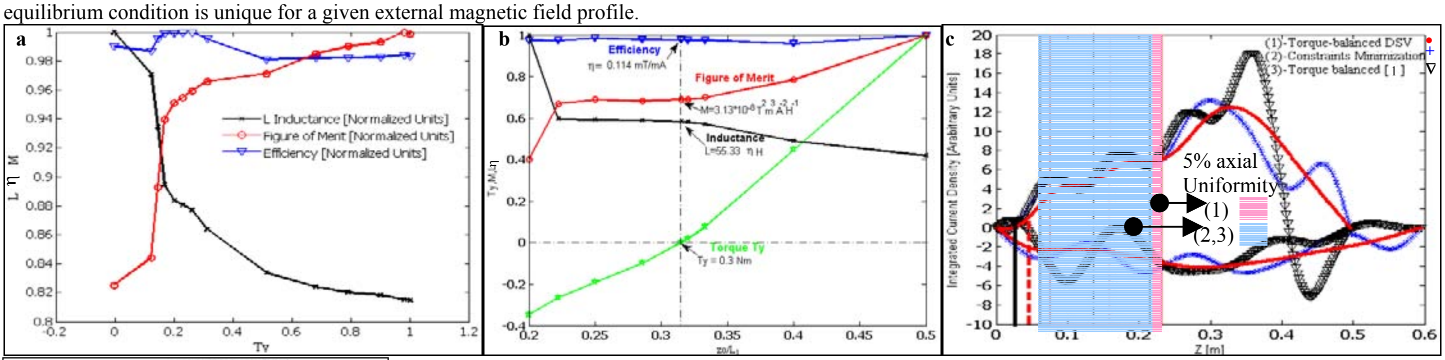
Introduction: The work describes design methods for target torque minimization for multi-layer, asymmetric, transverse gradient coils taking in account the magnetic field profiles of long and short bore symmetric and asymmetric magnets. It is well-know that an undesired net torque is produced due to the asymmetric nature of Lorentz force generated by the interaction between the static main magnetic field and an asymmetric head gradient coil. Different strategies to minimize the net torque have been presented [1, for example]. These methods, however, can not control the expected minimum torque/force value and hence its influence over figure of merit $M=(\eta^2\rho_1^5)/L$ (η: efficiency [T/m], ρ_1: coil radius [m] layer 1, L: inductance [μH]). In some design methods the torque/force analysis is achieved without taking into account the real static magnetic field profile generated by the magnet. In this work, we present two ways to minimize the net torque/force in asymmetric gradient coils. A target torque minimization strategy is introduced which can control the expected M value given target torque/force constraints. For example, we demonstrate that a reduction of up to 80% in net torque decreases the figure of merit by 5% from its maximum value. Simple current patterns for minimum torque, high performance head asymmetric gradient coils are obtained combining the external magnetic field effects over the gradient coil with a specific axial position of the gradient coil's linear region.

Method: The method assumes *N* layers of the current density $\mathbf{J}(\rho,\phi,z)$ flowing in concentric cylindrical surfaces of radii ρ_n. The $\mathbf{J}(\rho,\phi,z)$ is confined in the interval ($0\leq z\leq L_n$). $\mathbf{J}(\rho,\phi,z)$ in each layer is expressed as a sum of *Q* orthonormal functions multiplied by the amplitudes λ_{nq}. The target toque minimization strategy for asymmetric, multi-layer, transverse gradient coils is stated as quadratic programming under relaxed linear field conditions and linearly constrained torque/force generation [2]. Instead of balancing the constraints through weighting factors, we have introduced a non-uniformity error ε in order to control the M-gradient uniformity trade-off. In order to assure practical gradient coil solutions with high M-gradient uniformity-minimum torque trade-off, the torque/force is not constrained to a null value. The torque/force value is constrained between mechanical permissible fixed target values in each elemental area of the current density $\mathbf{J}(\rho_n,\phi,z)$. In our approach the torque/force produced in each elemental area $\mathbf{J}(\rho_n,\phi,z)$ is calculated taking into account the real magnetic field profile and the mutual magnetic field influence generated by all the axial harmonic modes of **J** in each elemental area of current density. To achieve our analysis we have taken in account a simple linear relationship that determines the axial coil length as function of DSV, coil diameter and target non-uniformity error to produce maximum M [2].

Results and Discussions: An asymmetric 2-layer transverse gradient coil for whole-body imaging was calculated using the method described in [2]. The coil radii were set to ρ_1=34 cm, $\rho_2=1.3\cdot\rho_1$, respectively. The DSV and the non-uniformity error ε were set to $0.5\cdot\rho_1$ and 7.5%, respectively. The corresponding optimal coil length to produce maximum M was L_1=1 m and L_2=1.2 m, respectively [2].The torque/force minimization was not included at this stage. The torque/force was calculated assuming the same coil configuration placed in three different 1.5 T magnet bores [3] while matching the magnet's DSV with the gradient coil's DSV: long [$F=7.3\cdot10^3$ N,$T=6.3\cdot10^3$ Nm], short [$F=8.5\cdot10^3$ N,$T=7.3\cdot10^3$ Nm] and asymmetric [$F=2.7\cdot10^3$ N,$T=2.5\cdot10^3$ Nm]. For a perfectly homogeneous magnetic field: F=0 N, $T=4.3\cdot10^3$ Nm. Note that a large error is introduced in the torque calculation when the main magnetic field is assumed to be perfectly homogenous. Actually the most common asymmetric gradient coils are designed for head imaging in long and short symmetric magnet bores where a relatively small yet undesirable torque persists. For a 2-layer asymmetric transverse gradient coil obtained in [2], the M value is $2.92\cdot10^{-8}$ $T^2m^3H^{-1}A^2$ and the resulting torque was calculated assuming a 1.5 T short bore magnet [F=37.27 N, T=37.09 Nm]. In order to study the torque effect over the figure of merit M we have constrained the absolute torque from different values in the range between 0 to 37.09 Nm. Applying our target torque minimization technique we find that if the torque is reduced up to 80% (see Fig 1**a**), the M value decreases only 5%, however for torque reduction larger than 81% the winding complexity increases incrementing the coil inductance and hence small M values are obtained. Varying the axial offset position of the gradient coil's DSV (z_0) we note that there is an axial z_0 value where the gradient coil is balanced producing zero net torque. Fig. (1**b**). This equilibrium condition is unique for a given external magnetic field profile.



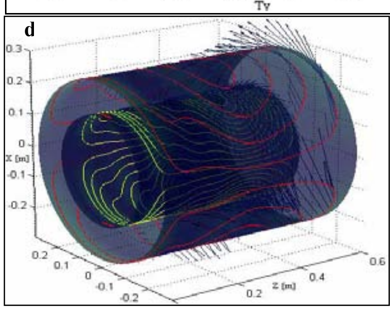


Fig. 1. Figure of merit, versus torque minimization (**a**). Gradient coil DSV position as function of torque, M, η and L (**b**). Three integrated current density profiles (**c**). (, coil edge (1, 2&3)). Coil pattern and torque profile (**d**).

Gradient coil balanced (1) under this condition presents a smooth current pattern (Fig. 1 **d**) and potentially this coil can reduces the Peripherical Nerve Stimulation (PNS) due to the negative turns that appear at the coil edge as an effect of coil balancing, by up to 1.12 times. The limitation of this technique is that this position could be outside of the target FOV. At this position, M is reduced by 30% from maximum value and for target torque technique (2) the M value is reduced 82% when the torque is reduced to zero. The advantage of the technique (2) is that the gradient coil DSV can be placed at any axial position and the torque can be minimized for this z_0 axial value. Subtracting an appropriate linear term from **J** we can produce a torque-balanced coil (3) [1]. The remaining torque is 5 times larger than the torque produced by the techniques (1) and (2). An increase in the number of layers produces a high torque-M trade-off. In future work we will study the effects of the intermediary layers and their influence in torque balancing.

Conclusion

In this work we have studied the torque minimization influences for head asymmetric transverse gradient coils taking into account external magnetic field effects. The target torque minimization technique permits control over the desired Figure of Merit value and the generation of torque-balanced, high performance, asymmetric transverse gradient coils. Combining the external magnetic field profile with a certain axial position of the gradient coil's linear region, it is possible to produce head asymmetric gradient coils with a minimum net torque.

References.

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