Novel design method for gradient coil structures with reduced acoustic noise characteristics

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Introduction

It is not only a need for improvement of image quality that provides new challenges in the design of high performance gradient coils. Magnetostimulation (dB/dt) as well as acoustic noise are two other target areas on which researchers are focusing their efforts in order to design patient friendly and safe gradient coil structures. It has been shown [1,2] that the gradient coil cylinder is the main source of the acoustic noise, followed by the main magnet's "warm bore" to a somewhat lesser extent. The noise generated by the vibration of the gradient cylinder is due to periodic Lorentz forces caused by the interaction between the current of the gradient coil and the main magnetic field [3]. This interaction generates a wide spectrum of resonant frequencies of the gradient tube that is directly related to the electromechanical characteristics of the gradient structure. Amongst the proposed solutions to the acoustic problem are the encapsulation of the gradient tube in a vacuum mounted separately from the system [1], the addition of sound dampening materials that are incorporated into the gradient coils structure [2], and the installation of an extra conductive shield surrounding the gradient structure with the intent to reduce the acoustic noise generated by either the gradient coil or the 'warm bore.' However, modification of gradient coil current patterns has not been considered in minimizing the acoustic noise and it is this degree of freedom that is addressed in the present paper.

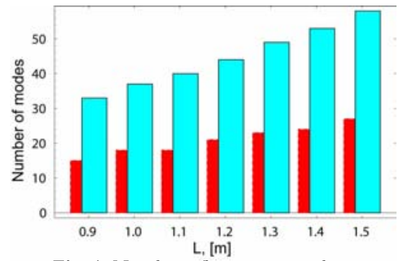

Fig. 1. Number of resonant modes as a function of gradient length. ("red" –modes up to circumferential wave number 2, "blue" – all modes).

Theory

Figure 1 indicates the dependency on the mechanical resonant modes for a cylindrically shaped gradient coil as a function of the gradient total length [4]. It is very challenging to design a whole body gradient coil with a very short mechanical length, preferably less than 1 m. In order to consider a ultra short gradient coil, a 3D gradient coil configuration [5] is assumed in this paper.

Employing the approach [5], we employ radial return paths at the end of the coils and a 3D gradient coil configuration is thereby generated. Regarding the acoustic noise, the general system of 3 inhomogeneous equations of vibration (in Flugge's approximation) are considered with external Lorentz driving forces resulting from the interaction between the main magnetic field and the x, y and z gradients [6,7]. The spectrum of normal modes is calculated and verified with FEM software Abaqus™. The general formula for calculating the average power for all three gradient coils is

$$\langle P\rangle = 4\beta\omega_R^2\rho L^2h^3\sum_{n=0}^{n_{\max}}\sum_{m=1}^{m_{\max}}\sum_{l=1}^{\infty}\frac{l^2\omega_{mn}\left|g_{z,mn}c_{z,l}+g_{y,mn}c_{y,l}+g_{x,mn}c_{x,l}\right|^2}{\left(\omega_{mn}^2-l^2\omega_R^2\right)^2+\left(2\beta l\omega_R\omega_{mn}\right)^2} \qquad (1)$$

where ω_{mn} are the normal modes of the cylinder, $\omega_R = 2\pi/T_R$ (T_R is the repetition time for experiment), m and n corresponds to axial and circumferential wave numbers, respectively. In addition, $g_{x,mn}, g_{y,mn}, g_{z,mn}$ represent the Fourier transforms of the Lorentz forces with respect to φ and z via

$$g_{(x,y,z),mn} = \frac{1}{2\pi}\int_{-\pi}^{\pi}e^{-in\varphi}d\varphi\int_{-L/2}^{L/2}e^{-imz}dz\left\{j^a_{(x,y,z),\varphi}(\varphi,z)B^a_z(z)+j^b_{(x,y,z),\varphi}(\varphi,z)B^b_z(z)\right\} \qquad (2)$$

where $j^{a(b)}_{(x,y,z),\varphi}$ are φ components of the current densities and $B_z^{a(b)}(z)$ is the main magnetic field on radius a (b).

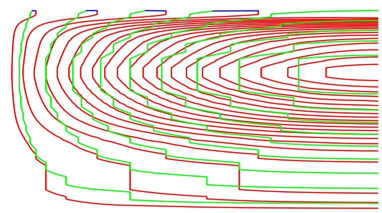

Fig.2. Octant of the MRI transverse gradient coils (3D design): Conventions: "red"-primary,"green"-secondary, "blue"-radial return segments.

Furthermore, the Fourier series coefficients $c_{x,l}, c_{y,l}, c_{z,l}$ are defined through $T_{(x,y,z)}(t)=\sum_{l=-\infty}^{\infty}c_{(x,y,z),l}e^{il\omega_R t}$ the corresponding pulse time sequence with the repetition time T_R characterizing the temporal behavior of the read, phase encoding, and slice selecting gradients, respectively. Mechanical characteristics are given by the gradient length L, thickness h, density ρ, Young's and Poisson's moduli, E and ν, and damping constant β. Employing the target field approach for an actively shielded 3D gradient coil configuration to minimize the average acoustic power of the gradient system, a modified current pattern for transverse and axial gradient coils emerges.

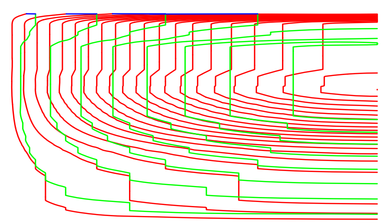

Fig. 3. Octant of the transverse gradient after vibro-acoustic power minimization. (For color convension see Fig. 1)

Results and Discussion

A 3D actively shielded X transverse gradient coil with minimized vibro-acoustic noise has been designed as an illustration. Specifically, the overall mechanical length of the gradient cylinder is chosen to be 90 cm, its external diameter as 89 cm and its mechanical internal diameter as 65 cm, Three constraint points are chosen to establish the quality of the gradient field inside a 40cm radial distance by 35cm axial distance DSV. The first constraint point is the setting of the gradient field strength to 30 mT/m while the other two constraint points define the linearity of the gradient coil to lie within 10% of its ideal value and the nonuniformity within 20%. Young's modulus is considered to be 2.8 10^9 Pa, the Poisson modulus 0.39, and the density of the material 4388 kg/m^3. The behavior of the main magnetic field of 1.5 T in the vicinity of the primary and secondary gradient coils is estimated using a realistic main magnetic field . Applying the target field approach to the set of aforementioned constraints, the corresponding discretized current pattern is generated. The estimated acoustic noise generated by such a design is calculated to be 115 dB. With the average acoustic power as the minimizing functional in the target field approach, the corresponding discrete current patterns for both gradient coils are found and shown in Fig. 3. The gradient field linearity and uniformity for the gradient coil with reduced acoustic noise was improved from 10% to 7% and from 35% to 25%, respectively. Therefore it is feasible to obtain nontrivial reductions in the acoustic noise of the gradient coil with little penalty, or even an improvement, to its field behavior. Acoustic noise reduction can become more significant for field strengths of 3.0 T and higher and especially for gradient field strengths that exceed 40 mT/m.

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