Design of a Low Joule Heating Gradient Coil Conductors

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Introduction

Driving currents of gradient coil causes temperature rise of itself. Generally, to reduce Joule heating, gradient coils are designed to minimize the resistance or the maximum current-density of the current paths. Nevertheless, in some cases, using high gradient slew rates, strength and frequency sequences (e.g. EPI) are restricted by temperature rise of gradient coil. In this case, the temperature rise is caused by eddy currents as well as driving currents. In this paper, a computation code based on FEM was applied for calculation of current flow on gradient coil conductors. In the high frequency gradient fields (over 500Hz), eddy current appeared remarkably on wide conductors. We find narrow conductors can effectively reduce the eddy currents, and we confirmed the effect of heating suppression by the experiments.

Methods

Fig. 1 shows part of computational model. The gradient coil was designed using original computational tool DUCAS[1]. Though, the size of the gradient coil is usually the order of 1 meter, the size of conductor is less than few centimeters. The evaluation of current distribution is needed more than 1 million finite elements. Therefore, finite element meshes applied only for the region of interest, another part of conductors are modeled by line current models. On the edges of finite element model, driving current are applied. At the same time, magnetic fields are applied in phase with line current models. The thin conductor method[2] is used for eddy current analysis, shown as Fig. 2, to reduce the unknowns and spatial finite elements. Where J_s is surface current density as integrated over the thickness, T_n is current potential, *i*, *j* and *k* correspond to the points of element, respectively, and $\boldsymbol{n}$ is the orthogonal vector of element. Using current density $\boldsymbol{J}$, current vector potential $\boldsymbol{T}$ is defined as eq. (1). If the conductor thickness is thinner than skin depth of current density, the thin conductor method is valid and unknowns are reduced from 3D vector $\boldsymbol{J}$ to scalar potential T_n as eq. (2).

Results

We applied above methods for planer gradient coil conductors. Fig. 3 (a) and (b) shows calculated current flow lines of Y gradient main coil. (a) is wide conductor coil, (b) is narrow conductor coil (conductor width <10mm), respectively. Each current flow line shows 20A respectively. The Y gradient coil is semicircle cupper sheet (thickness 3 mm). The driving current waveform is sinusoidal (frequency=1kHz, amplitude=100A_{pk}). In case of (a) wide conductors, eddy current cased by gradient magnetic field appears remarkably in the high gradient magnetic field region. While the driving current is 100A, eddy current generated up to 180A. On the other hand, (b) narrow conductors suppress the eddy current. Experimental results (c) and (d) shows thermal imaging for same part of (a) or (b) (after 50 min). Experimental gradient coil was a mock up, but constructed with set of main and shield coils as the actual (without cooling system). Coil conductor is formed by grooving. The driving current wave form was sinusoidal (frequency=500Hz, amplitude=88A_{pk}). In case of (d), narrow conductors suppress temperature rise of conductors. It has been found that the temperature distribution corresponding to the eddy current distribution.

Discussion and Conclusion

The eddy current is induced by time-varying gradient magnetic field, and therefore it appears strongly in near the center of the turn. However, this area is different from maximum current-density area. For minimizing the grooving, conductor width is wider. Wide conductor has low resistance for DC, but generates a large eddy current for AC. On the other hand, narrow conductor can suppress eddy current induced by gradient magnetic field. DC current-density of the narrow conductor area is less than the maximum current-density area, and increased resistance and heat generation of DC are negligibly small for the entire gradient coils. In addition, because of the gradient magnetic field is almost zero in the shield coil, eddy current in the shield coil is small regardless of the conductor width. This approach has already been applied to the actual gradient coil design.

References

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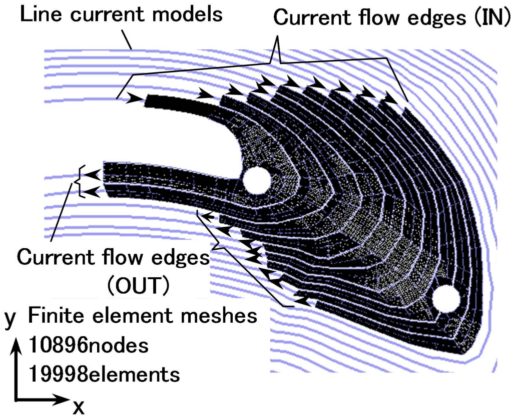


Fig. 1 Finite element meshes and line current models. (Part of Y gradient coils)

$$\boldsymbol{J} = \nabla \times \boldsymbol{T} \qquad \ldots(1)$$

$$J_s = \nabla T_n \times \boldsymbol{n} \qquad \ldots(2)$$

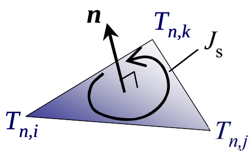
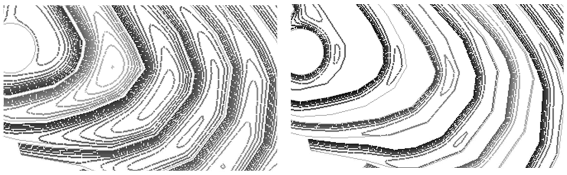
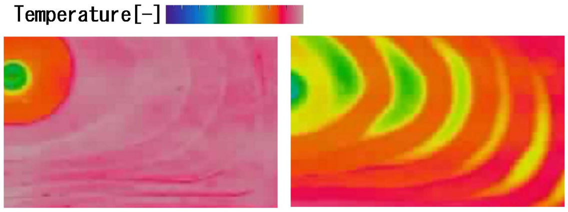


Fig. 2 Description of the thin conductors method



(a) Wide conductors (b) Narrow conductors



(c) Wide conductors (d) Narrow conductors

Fig. 3 Current flow lines by calculation (a), (b) and temperature rise by experiment (c), (d).