The Optimized Scheme of Performance Parameters of Gradient Coils for Permanent Magnetic Open Architecture Nuclear Magnetic Resonance System

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Abstract—**In view of Magnetic Resonance Imaging(MRI) gradient coils is the directly determining factors of imaging quality and high-end application field requirements. Based on optimization theory about gradient coils performance index, Construction of the optimized scheme of Nuclear Magnetic Resonance gradient coils performance parameters and performance index testing platform, which is include back-stepping design by Matlab and the simulation of electromagnetic field distribution with Ansoft, and the design of geometric structure and electric inductance, etc. performance parameters for permanent magnetism open architecture plate gradient coils （x、y、z）, in order to satisfy with gradient field intensity, functionally gradient linearity, slew rate, gradient variation of inductance, etc. performance parameters for gradient coils. Experiment results show the scheme has some practical value in engineering.**

Key words-Magnetic Resonance Imaging; Gradient Coils; Matlab/Ansoft; Gradient Magnetic Field; Eddy Current

I. Introduction

The permanent magnetic nuclear magnetic resonance was identified as a focus on supporting the development of industrial equipment by China National Development and Reform Commission; there are many advantages, such as relatively low cost price and low operation and maintenance. Therefore, the permanent magnetic nuclear magnetic resonance currently occupy the low-end domestic market and has been exported more than 50 countries, was contributed to improve the diagnosis of related diseases. Magnetic resonance imaging system mainly consists of the magnet system, the gradient field system, RF (Radio-Frequency Field) system, the spectrometer system and computer system of five parts. Magnetic resonance imaging gradient field is the key parameters to determine the MRI system performance, and the gradient coil is an important component of gradient field in magnetic resonance imaging system, which directly determines the performance of image quality. In recent years, the increasing pressure of low-field NMR equipment comes from high-field MRI equipment costs decrease and high-end application development. Thence, low-field magnetic resonance equipment need to gradually expand the high-end application technology while maintaining the traditional advantages. However, the developed high-performance gradient coil is the most important part of expanding high-end applications. As with the low field permanent magnetic structural features, open MRI systems are used dual-plane gradient coils, aim to generate each of the three mutually orthogonal gradient magnetic fields (level selection, phase encoding, frequency encoding), so as to provide location based for image reconstruction. High-performance permanent magnet open MRI gradient coils research is an important part of developing more competitive permanent magnetic resonance imaging (MRI) equipment.

At present, the highest index of foreign production enterprises manufacturing nuclear magnetic resonance gradient coil system is about: gradient field intensity, 20mT/m, gradient switching rate, 80mT/m/ms, gradient linearity (40cm DSV), ≤ ±5%. The wire wound type gradient coils is mostly used in domestic, the maximum gradient field intensity, 12mT/m, gradient switching rate, 25mT/m/ms, which can not meet a number of high-performance applications. From in terms of the expansion of the application of NMR magnet, It is very important to improve the gradient coils performance index for the development of nuclear magnetic resonance of t has a great significance.

II. The Key Performance Parameters Index of Gradient Coils

Generally, the gradient magnetic field system consists of the gradient coils, gradient controller, gradient amplifiers and other components. Gradient magnetic field in the imaging area,

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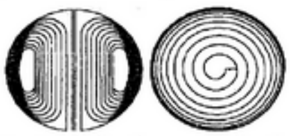
according to the requirement, dynamically add a x 、 y 、 z three-dimensional orthogonal linear magnetic gradient field in the main field, that subjects the body in different locations have different resonant frequencies, to achieve the level selection, phase encoding and frequency encoding of imaging voxel. Primarily for meet the requirements of linearity, fast



x or y axis direction z axis direction

Fig.1 Sketch of the gradient coils

switching of the gradient magnetic field for magnetic resonance equipment. A component of ground magnetic field inspired by the coil power along the main magnetic field direction, the modulus of the magnetic field component is a linear relationship at the coordinates direction of x 、 y 、 z , referred to the corresponding coil were called x 、 y 、 z gradient coils. Figure 1 indicates the direction of y and z gradient coil, direction of the x gradient coils and the y gradient coils difference between geometric coordinates of 90°. In order to achieve the organization's spatial orientation, need to superimpose a field intensity distribution of the magnetic linear of the center of the static magnetic field to the origin of coordinates on the main uniform magnetic field coordinates, figure 2. Three-dimensional gradient magnetic field generated by constantly switching between connected and disconnect of the three gradient coils, magnetic gradient coils are installed in the main magnetic body, by the gradient of the power generator and power amplifiers provide pulsed current to work.

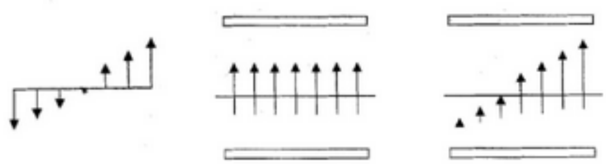
technical indicators, which are the direct reflection of the quality and speed of MRI imaging. In the process of permanent magnetic resonance imaging, phase gradient magnetic field and the level selection gradient magnetic field must be fast switched off before read out the gradient magnetic field gradient former connected. Sometimes the polarity gradient field will be quickly converted, So the gradient filed intensity, gradient linearity, switching rate, gradient inductance and gradient energy supply of the gradient coils should be have strict requirements, such as follows:

A. Gradient Field Intensity

Three sets gradient coils generate the gradient field in the axis x 、 y 、 z direction, the size of the magnetic filed gradient (the magnetic field intensity changes at per unit length) will affect the sampling thickness of layer, minimum scan field of view (FOV) and spatial resolution. When the bandwidth of RF center is selected, the smaller the gradient field intensity, the more thickness of the corresponding selected layer. Gradient field intensity $B_G = B_0 + \frac{\Delta B}{\Delta L}$ will increase, thin layer, multi-layer scanning and small field of vision (FOV) scans can be realized.

B. Gradient Magnetic Field Linearity

The gradient magnetic field linearity is the slope gradient of the magnetic field intensity changes (units: mT/m) to describe, is defined as: $\lambda = \frac{\gamma_{max} - \gamma_{min}}{\gamma_{ave}}$, where, γ_{max}、 γ_{min} and γ_{ave} are respectively to be delimited as the maximum, minimum, and their average of the slope of the gradient magnetic field intensity changes in the domain of all points. The greater the slope, the thinner the slice thickness can be obtained. Gradient magnetic field linearity is one of the factors of the quality of gradient magnetic field, directly affect the geometric distortion



(a) Linear gradient ΔB (b) Static magnetic field B_0 (c) magnetic field superposition

Fig.2 Principle of superposition of magnetic field gradient

Gradient magnetic field refers the linear changes in magnetic field intensity along the Cartesian coordinate system in a coordinate direction. That is, the magnetic field intensity is linear increasing or decreasing at per unit length for the gradient field. The most important guideline to measure gradient system is gradient field intensity and switching rate, the former characterization of the change in magnetic field intensity with spatial extent, the latter reflects the rate of the magnetic field change with time. Therefore, the gradient magnetic field performance is good or bad, the level of

of the image, what is more, if the gradient linearity is not good, circular samples may be non-circular image, thereby affecting the diagnosis of lesions. When the gradient field intensity non-linear changes in both sides of the magnet center, the signal intensity of the image can not be linear coded along the direction of phase encoding and frequency encoding, this image will be deformed, which mainly show that the compression distortion in the anatomic site at the edge of the scanning field of vision (FOV). Ideal gradient field can not make the image produce distortion. The human body imaging, diversity of head tissue, fine structure, and imaging requires high. For example, the required sphere space Φ 300mm diameter in the diagnosis of head, the required gradient magnetic field linearity is no more than $\pm 5\%$.

C. Gradient Switching Rate

Gradient switching rate is a very important indicator for evaluating the gradient field system, which is expressed that the speed of the gradient coil achieves the required gradient magnetic field intensity (unit: (T/m) /s or (mT/m) /ms), switch rate increases, the gradient changes fast, so the shorter imaging time, the more able to meet the high-end applications. Switching rate is the ratio of the maximum gradient field intensity and the time of gradient field intensity from zero to the maximum gradient field intensity, when the gradient field intensity is fixed, that the ratio actually reflects the slope of any point's tangent on the curve in the gradient field. When the gradient field changes, the scanning sequence is in a wait state, the switching rate increase, time of echo (TE), time of repetition (TR) can be achieved to a minimum, meaning that can further improve the scanning speed, It has a great advantage especially during the single-shot echo planar imaging (EPI) scan. At the same time the switching rate index is a key determinant of expansion of functional imaging. But the switching rate can not be increase indefinitely. Because the higher the switching rate is, the greater magnetic field intensity rate of change over time(dB/dt), while the rapidly changing magnetic field generates an electric field in the surrounding electric field (Faraday's law of electromagnetic induction), so that the patient is a conductor will generate current flows through, caused severe peripheral nervous system (PNS) muscle stimulation, and have some of the threat of patient safety. However, in the situation of high switching rate, limiting the scan view can be ensure that the rate of magnetic field intensity change over time ($\frac{dB}{dt} = L\frac{di}{dt}$) is unlikely too large.

D. Gradient Inductance

Eddy current is other important MRI parameters, which is critical to image quality: because in the process of magnetic resonance imaging, electromagnetic coils which produce the gradient magnetic field should be highly frequent interruption, the switching off and on of the gradient coil will be produce inductance and mutual inductance, which would be induces eddy current in the electric conductors easily. Accordingly, it causes the suppression of the rapidly changing gradient magnetic field, and impeding the normal imaging process. It is generally necessary to use a dedicated eddy current technology to remove the eddy current. The working current of the gradient coil is a pulse current, to make the leading edge steep rise in front and speed up the imaging speed, requiring smaller gradient coil inductance. Therefore, minimized the gradient coil inductance has a very important significance under the premise of meeting other performance requirements, the total inductance of a set of gradient coils usually require no more than 0.9mH.

III. The Overall Program on Optimization of Gradient Coil Key Performance Parameters

A. The Overall Program on Optimization of Gradient Coil Performance Parameters

Figure 3, The general framework of optimized scheme of key performance parameters to gradient coils, It is a unique design method of gradient coil through a combination of theoretical analysis and Matlab/Ansoft simulation software (Matlab achieve inversion design, Ansoft simulate the magnetic field), It can obtain the high-performance

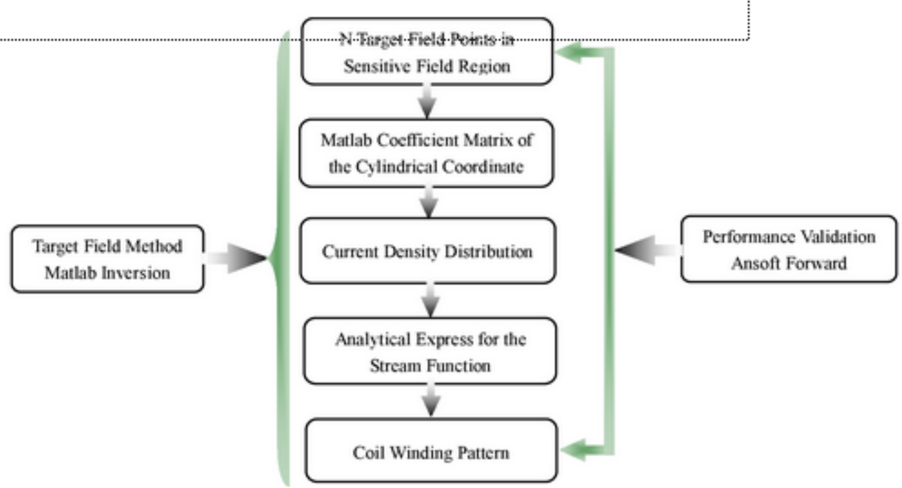


Fig.3 The General Framework of Optimized Scheme of Key Performance Parameters to Gradient Coils

specifications of the gradient coils in the current permanent magnet open MRI system, the indicators can be achieved gradient magnetic field intensity: 30 mT/m (in the x 、 y 、 z axis directions); gradient switching rate: 24mT/m/ms; gradient linearity: ≤ ± 3.8%(in the x 、 y 、 z axis directions), design a good performance gradient coils in order to produce a better linearity gradient field, thereby enhancing the gradient of the magnetic field intensity and switching rate, shorten the echo time (TE) and repetition time (TR), to speed up signal acquisition speed, and improve gradient system noise ratio (SNR), then improving the image quality and imaging speed of MRI system. According to Biot-Savart Law (calculated the magnetic field intensity which produced at any point in space for a finite conductor), design using the following method: target field method (inversion), to calculate the required current density distribution through pre-defined the magnetic field distribution in the sensitive area, then to obtain the analytical expression of the stream function, further stimulate the coil winding pattern. Detailed design process: *a)* select N points of target area in the sensitive field; *b)* Calculated the coefficient matrix using Matlab in cylindrical coordinates; *c)* resulting the coil winding by putting it into the stream function expression as well as current density expression; *d)* Finally, carry out the simulation evaluation: ① the gradient field linearity depends on the accuracy of the gradient magnetic filed intensity equations; ② make the coefficient matrix back substitution to the Biot-Savart Law expression, then compare the intensity of the magnetic field with the intensity of the target field:

$$\lambda = \left| \frac{B_{z,i} - B_{zidea,i}}{B_{zidea,i}} \right| \times 100\% \tag{1}$$

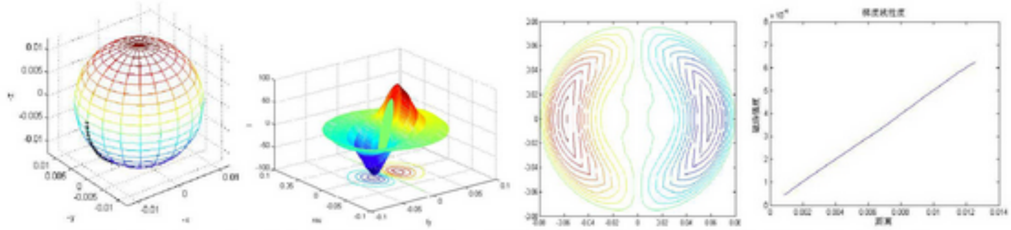
Where, λ —Gradient magnetic field linearity; $B_{z,i}$ — Calculated magnetic field intensity, mT/m; $B_{zidea,i}$ — the corresponding target field magnetic field intensity, mT/m.

B. Proposed Solution of the Key Technical Problems for Gradient Coils Performance

The gradient coil is an important component of gradient magnetic field system for Magnetic Resonance Imaging, the gradient magnetic field intensity, linearity, switching rate, gradient inductance, and other performance parameters of the gradient coils restrict the image quality to a large extent, and its function is to generate the gradient magnetic field for spatial coding, magnetic field intensity has a linear relationship with the space coordinates. Based on the above technical requirements, proposed solution of the key technical problems for gradient coils performance include:

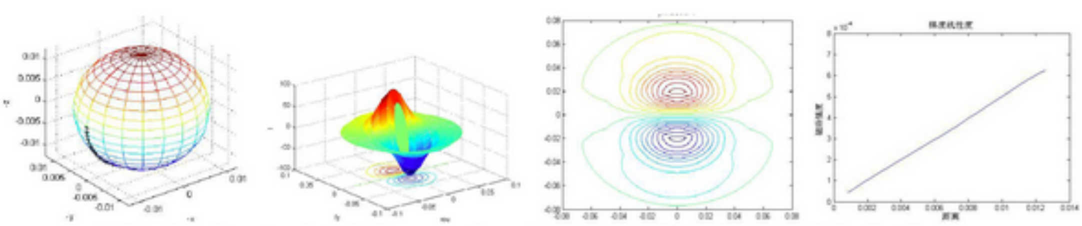
1) Performance Parameters Optimization: it design the gradient coil by the combination of theoretical analysis and Matlab/Ansoft software simulation method, which will obtain a high-performance specifications of gradient coil to permanent magnet open MRI system at the present stage, as shown in Figure 4 to 6, parameters optimization of x , y , z gradient coil performance, indicators is expected to reach: 30mT/ m (x , y , z axis direction); gradient linearity: ≤ ± 3.8% (x , y , z axis direction); gradient switching rate: 24 (mT/m)/ms.

2) Reducing the Eddy Current Problems: the gradient inductance is the main lend a side eddy. The size of the eddy produced by the gradient is proportional to the $L\frac{di}{dt}$, in the same request of switching rate, the smaller the gradient inductance L of coil is (that the smaller the gradient coil power), the less image affect by the eddy.



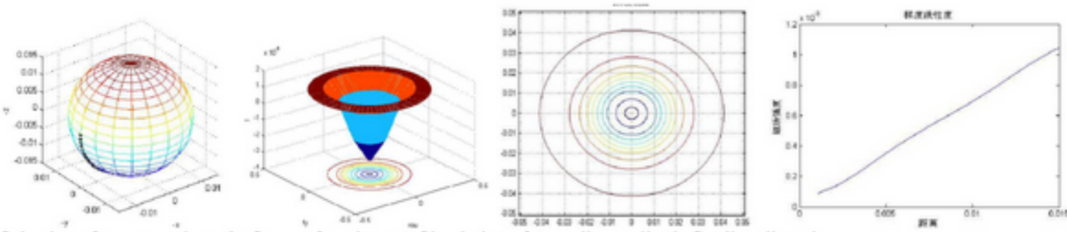
(a) Selection of target market (b) Stream function (c) Simulation of x gradient coil (d) Gradient linearity

Fig.4 Parameter optimization of x gradient coil performance



(a) Selection of target market (b) Stream function (c) Simulation of y gradient coil (d) Gradient linearity

Fig.5 Parameter optimization of y gradient coil performance



(a) Selection of target market (b) Stream function (c) Simulation of z gradient coil (d) Gradient linearity

Fig.6 Parameter optimization of Z gradient coil performance

IV. CONCLUSION

The program is based on the optimization theory of the gradient coils performance parameters for common permanent magnetic open architecture Nuclear Magnetic Resonance system. It design the high-performance gradient coil by the way of the combination of theoretical analysis and Matlab/ Ansoft software simulation method, meanwhile, coil design according to the minimum energy principle, which can reduce the eddy generated by the coil inductance (self and mutual inductances), improving the signal to noise ratio (SNR) of magnetic resonance imaging system, thus ameliorating MRI System's image quality and imaging speed. At the same time, study is based on the operating conditions test results of gradient coils in the manufactures practical application, and construction of the gradient coils performance index testing platform, which include the gradient field intensity, switching rate, gradient linearity, gradient coil self-inductance and mutual inductance, gradient coils operating current, etc. The testing platform will provide reliable basis for the design and manufacture of the medical magnetic resonance imaging equipment gradient coils.

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REFERENCES

[1] Wang Hong-zhi, Zhang Xue-long, Li Geng-ying. Design of the Shim Coil to the Permanent Magnetic Micro-MRI[J], Journal of Biomedical Engineering, 2009,26(3):465-470.

[2] Zhou Tao, Zhang Jia-xiang. Open-magnetic Design[J], Chinese Journal of Medical Instrumentation, 2000,24(4):203-205.

[3] Larry K. Forbes, Stuart Crozier, Novel Target-Field Method for Designing Shielded BiplanarShim and Gradient Coils[J], IEEE TRANSACTIONS ON MAGNETICS, 2004, 40(4):1930-1937.

[4] Liu Ruo-qian, Huang Chang-gang. The Relationship between the Magnetic Plate Size and Gradient Coils of the Permanent Magnetic Resonance Imaging [J], Electrical Engineering and Energy, 2000, 12(6):14-19.

[5] Wang Hong-zhi, Tan Zhi-guang, Zhang Xue-long. Developed the Sensitive Micro-RF Coil for Desktop Magnetic Resonance Imaging device[J], Chinese Journal of Medical Instrumentation, 2008.1(33):35-39.

[6] Wu Ke, Cong Jian-bo, Xian Hong, Wang Chang-zhen, Sun Cun-pu. L-band ESR Imaging and Three-dimensional Gradient Magnetic Field[J], Journal of Magnetic Resonance, 2002,19(4):337-339.

[7] Wang Hong, Lin Qing-de. Permanent Magnetic Type MRI Technology Discussion[J], Chinese Journal of Medical Instrumentation, 2001,21(2):72-75.

[8] Wang H.Z, Zhang X.L, Wang Y, et al. The emulation of nuclear magnetic resonance imaging heory using Matlab. Shanghai: The 2nd IEEE/ICBBE international conf on biomedical and bio-information engineering, 2008.5.(Indexed by EI,Accession number:083711531998).

[9] Xu Wen-long, Tao Gui-sheng, Xia Ling. Simulation of the human Heart Induced Eddy in the MRI Gradient Magnetic Field[J], Journal of the China Metrology Institute, 2005,16(3):195-198.

[10] Wu Hai-cheng, Liu Zheng-min, Zhou He-qin. Study of the Design Method to Permanent Magnet[J], Chinese Journal of Medical Instrumentation, 2006,30(3):176-179.

[11] Yan Xiao-long, Xie Hai-bin, Bian Ming-hua, Li Geng-ying. A General NMR Mcrio-Imaging System[J], Journal of Magnetic Resonance, 2000,17(6):433-437.

[12] Wang H.Z, Zhang X.L, Wu Jie. Magnetic Resonance Imaging Test Tutorial [M].Science Press, 2008.1.

[13] R Turner. A target field approach to optimal coil design [J]. Phys. D: Appl. Phys. 1986,19: L147-LI51.

[14] Bai Hua, Wang Qiu-liang, Yu Yun-jia, Xia Ping-chou. Spherical Coil Design Based on the Target Field Method[J], Journal of China Motor Engineering,2004,24(6):132-135.

[15] Peter T, While a, Larry K. Forbes a, Stuart Crozier. 3D Gradient coil design–toroidal surfaces[J], Journal of Magnetic Resonance,2009,1:1-10.

[16] Crozier S., Doddrell D.M. Gradient-coil design by simulated annealing [J].I.A Jagn. Reson. 1993,A 103, 354-357.

[17] Caparelli E.C., Tomasi D., Panepucci, H. Shielded biplanar gradient coil design. J. Magn. Reson. Imaging in press,1998.