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Design and Optimization of High Uniformity Magnetic Field Gradient Coil

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Abstract. The gradient magnetic field has been widely used in biomedicine and other fields. Electrical coils are often used in engineering to generate the required magnetic field. In practical application, the uniformity of the magnetic gradient coil has a great influence on the accuracy of measuring point positioning of the magnetic sensor. In this paper, the gradient uniformity is taken as the optimization goal, and the sequential quadratic programming (SQP) algorithm is creatively used to study the coil design and optimization method. Firstly, based on the design of the standard Helmholtz coil configuration, the parameters to be optimized are determined. The objective function of the magnetic field gradient uniformity is then established, and the objective function is iteratively optimized by the SQP optimization algorithm. Numerical simulation results show that the gradient uniformity of the magnetic field is greatly improved by optimizing the coil configuration.

Keywords. Gradient magnetic field; Coil design; Uniformity; Sequential quadratic programming algorithm

1. Introduction

The gradient magnetic field has been widely used in biomedicine and other fields. In engineering, it is common to use electrical coils and permanent magnets to establish a target gradient magnetic field. However, the magnetic field intensity and gradient generated by permanent magnets are difficult to control, and it is easy to lose the magnetic field during use. Therefore, in the actual production and application, the required magnetic field is established by the electrical coils. In addition to strength, there are usually requirements for magnetic field uniformity and magnetic field gradient indicators. For example, magnetic resonance imaging (MRI) systems need to superimpose longitudinal

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or transverse uniform gradient magnetic fields on a uniform constant magnetic field to obtain richer spatial imaging information [1]. These gradient magnetic fields are the key part of MRI technology, and the magnetic field gradient performance directly affects the image quality and the diagnosis result of the object. In addition, the gradient coil also can be used as a calibration equipment positioning precision of magnetic gradiometer, which is of great significance in earth science, aerospace, target detection, and other fields [2-4].

The uniformity of the magnetic gradient coil has a great influence on the measuring point positioning accuracy of the sensor. However, in the design process of the traditional gradient coil, the uniformity of the magnetic field gradient is less considered, resulting in the uniformity of the central working area is not ideal. In order to design and optimize the gradient coil, some special research has been carried out around the world [5,6]. In 1984, Edlstein et al. proposed a method to solve the current density distribution in the plane where the coil is located by constructing a specific flow function. In 1986, Turner et al. proposed a method that obtained the current density distribution by solving the set gradient field in reverse and then used the flow function to discretize the current density distribution. In 2010, Juchem et al. solved a gradient coil system composed of a group of coils by the Levenberg-Marquardt method. Later, Jia et al. called this type of gradient coil system matrix gradient system and studied the feasibility of generating a nonlinear gradient field. In 2018, Kroboth et al. regarded the design of matrix gradient coils as a generalized assignment problem and used a simulated annealing method to design matrix coils [7].

In this paper, based on the above research methods, the SQP algorithm is used for the first time to reduce the problem of solving the parameters of a multi-group gradient coil system to a nonlinear programming problem for iterative calculation, which greatly improves the uniformity of the gradient coil.

2. Design Principle of the Gradient Coil

At present, the Helmholtz coil and Maxwell coil are the most widely used coil forms. and have been widely studied in the bio-electromagnetic field. The conventional gradient field coils commonly used are anti-Helmholtz coils and gradient field Maxwell coils. This paper mainly studies the form of an anti-Helmholtz coil. Helmholtz coils are divided into rectangular Helmholtz coils and circular Helmholtz coils. The standard configuration of the two coils is shown in Figure 1.

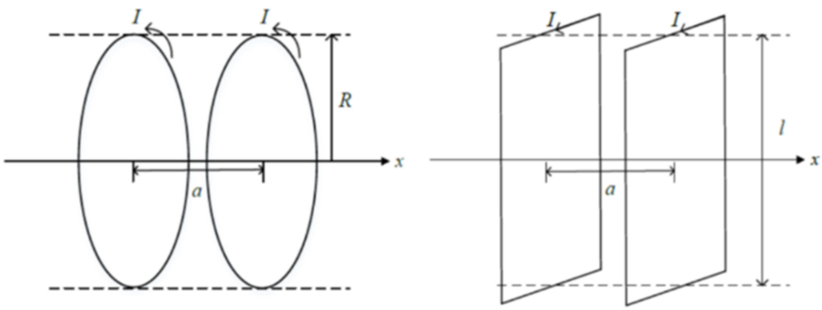

Figure 1. Rectangular Helmholtz coil and circular Helmholtz coil diagram

A circular Helmholtz coil is composed of two coils, the size of which is the same. The center of the circle is on the same axis, and the planes are parallel to each other. The radius of the coil is equal to the distance between the centers of the circle. The rectangular Helmholtz coil is composed of two rectangular coils with the same side length, the center on the same axis, and the plane parallel to each other, where the relationship between the axis distance a and the side length L is a=0.5445 L. A uniform field is generated between the coils when a current in the same direction and amplitude is applied to both coils of the Helmholtz coil. The anti-Helmholtz coil means that the two coils of the Helmholtz coil are passed with a current of opposite direction and the same amplitude, which generates a gradient magnetic field inside the coil.

However, when the traditional coil is designed, its structure and parameters are to establish a uniform magnetic field as the goal, and the gradient uniformity index after the change of power mode is not considered. Thus, the gradient uniformity of the coil center working area is not very ideal.

3. Coil Optimization Method

Gradient coil parameter optimization is an electromagnetic optimization process, in essence. The problem of calculating the parameters of the gradient coil can be reduced to solving the objective function coupled by the physical index (such as the field uniformity index, etc.) and the engineering constraint (such as the installation space of the coil, etc.). The objective function of coil optimization includes nonlinear functions, which is a nonlinear programming problem. At present, there is no general algorithm applicable to all kinds of problems in nonlinear programming, and all kinds of existing methods have their specific scope of application.

Among them, the SQP algorithm has the advantages of outstanding boundary searching ability, efficient computing speed, and good convergence of results in solving constrained nonlinear optimization problems. It has been widely paid attention to in engineering applications. The algorithm mainly solves the problem through the following steps. Firstly, the initial nonlinear optimization problem is transformed into a simple quadratic optimization problem by Taylor expansion. The second step is to search and solve the simple quadratic optimization (QP) problem iteratively. In the iterative process of SQP, each step needs to solve one or more QP subproblems.

Therefore, we creatively use the SQP algorithm to solve the problem of multiple groups of gradient coil system parameters reduced to a nonlinear programming problem for iterative calculation. Finally, we give the optimal coil structure, turns, and current parameters to achieve the desired field gradient uniformity index.

Rectangular coils and circular coils are the two most commonly used coil forms in engineering. In this paper, the parameter optimization of the uniformity index of magnetic field gradient distribution is studied by taking multiple groups of coaxial rectangular coils as an example. Figure 2 shows the four rectangular Helmholtz coil system and the magnetic field established by the discrete unit current element of the coil, with the coordinate origin in the center of the structure. The four coils have the same size, and in practical applications, the four coils are connected in series to ensure the synchronization of the excitation current.

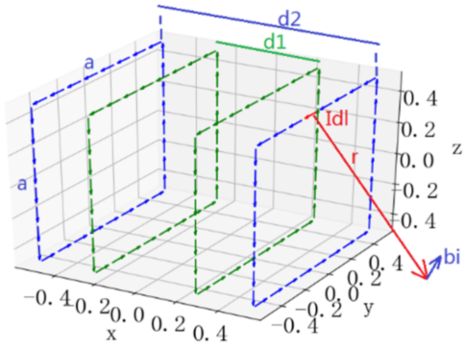

Figure 2. Four rectangular Helmholtz coils and discrete unit current elements produce a magnetic field diagram

In the coil optimization process, the magnetic field of the coil system at multiple spatial points in the optimization area should be calculated. There are many ways for rectangular coil magnetic field calculation. Among them, the analytical method is relatively simple in calculating the magnetic field along the axis, but the analytical formula for the vector of the axis is very complicated. When the finite element method is used to solve the space magnetic field of the large-size hollow coil, there is a great difference between the grid division of thin wires and the grid division of space points. This leads to too many discrete grid points, time-consuming calculations, and even the solution does not converge. In this paper, the discrete integral method is used to solve the magnetic field established by a coil at a certain point in space, the coil current is equivalent to the ideal line current model, and the coil is discrete into a tiny current vector unit. The magnetic field vector of each current vector unit at a certain space point is calculated by the Biot-Savart formula. Then the magnetic field vector generated by the discrete current vector unit on all coil groups can be obtained by the discrete integral summation of the magnetic field vector established by the whole coils at a certain space point. This method has high computational efficiency and is easy to be programmed. It can be extended to other arbitrary coils.

The optimization design process of magnetic field gradient coil is as follows: 1) The number of coil groups and parameters to be optimized are determined. With the increase of the number of coil groups, the variable parameters of coil optimization increase, which can greatly improve the optimization effect of the coil; 2) The objective function of magnetic gradient uniformity is given, and the boundary conditions of physical parameters are given according to the engineering practice; 3) The SQP optimization algorithm is used to iteratively optimize the objective function; 4) Coil turns are corrected, and the optimization calculation is performed again; 5) Numerical simulation verification index is conducted.

After calculating the optimal parameters of the coil system through the above process, it is also necessary to consider whether other engineering constraints meet the requirements, such as the cable resistance, the cable weight, the maximum power consumption, and so on. Due to the influence of machining precision, machining tolerance, and winding precision, the actual magnetic field gradient uniformity index may be deviated from the simulation result, so a certain margin should be left for the optimization calculation of the objective function.

4. Optimization Result

In this paper, the standard rectangular Helmholtz field gradient coil, the standard circular Helmholtz field gradient coil, and the optimized gradient field coil are simulated, respectively, and the corresponding magnetic field parameters are obtained.

For a standard rectangular Helmholtz field gradient coil, its parameter settings are as follows: side length is 2650 mm (the outer boundary of the engineering constraint), coil spacing is 1443 mm, coil turns are 30, and the current is 1 A. The field parameters are set to a cube area with a center side length of 1 meter. The coil simulation results are shown in Figure 3.

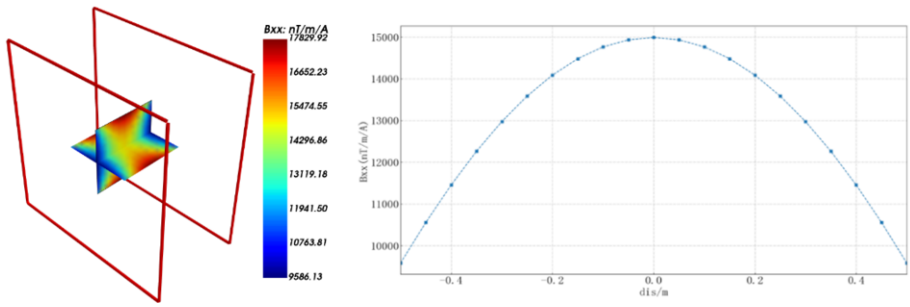

Figure 3. Rectangular Helmholtz gradient coil configuration and magnetic field gradient distribution in the central axis

Figure 3 shows the configuration of the rectangular Helmholtz gradient coil, the magnetic field distribution, and the variation of the gradient field on the central axis. The center of the magnetic field gradient value is larger, the two ends are smaller, and the maximum deviation rate is 35%.

For a standard circular Helmholtz field gradient coil, its parameter settings are as follows: diameter is 2650 mm (the outer boundary of the engineering constraint), coil spacing is 1325 mm, coil turns are 30, and the current is 1 A. The field parameters are set to a cube area with a center side length of 1 meter. The coil simulation results are shown in Figure 4.

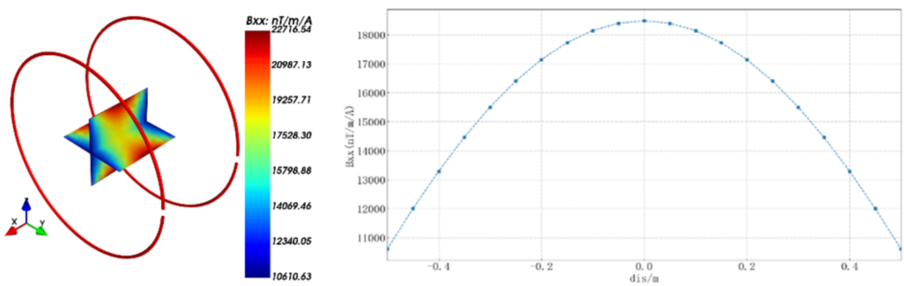

Figure 4. Circular Helmholtz gradient coil configuration and magnetic field gradient distribution in the central axis

Figure 4 shows the configuration of the circular Helmholtz gradient coil, the magnetic field distribution, and the variation of the gradient field on the central axis. The center of the magnetic field gradient value is larger, the two ends are smaller, and the maximum deviation rate is 43%.

According to technical requirements and engineering constraints, the optimized gradient coil system is composed of a set of rectangular coils and a set of circular coils. Its parameter settings are as follows: the rectangular coil side length is 2650 mm, spacing is 1850 mm, coil turns are 30, and current is 1 A. The circular coil diameter is 985 mm, spacing is 1850 mm, coil turns are 4, and current is 1 A. The field parameters are set to a cube area with a center side length of 1 meter. To facilitate manufacturing and reduce the difficulty of assembly, the circular coil group (shown in the red frame) is coplanar with the circular coil group (shown in the green frame). The coil simulation results as shown in Figure 5.

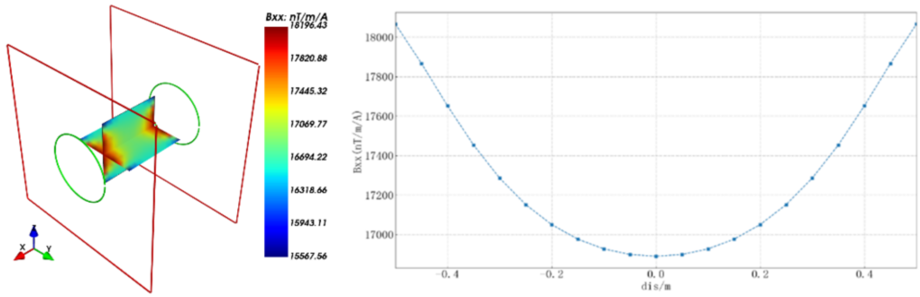

Figure 5. Optimized Helmholtz gradient coil configuration and magnetic field gradient distribution in the central axis

Figure 5 shows the configuration of the optimized gradient coil, the magnetic field distribution, and the variation of the gradient field on the central axis. The center of the magnetic field gradient value is smaller, the two ends are larger, and the maximum deviation rate is 7%.

Compared with the above three sets of simulation results, it is shown that the gradient uniformity can be greatly improved by optimizing the configuration and coefficient of the gradient coil.

5. Conclusion

This paper takes the standard Helmholtz coil configuration as the design basis and the gradient uniformity as the optimization objective function. It creatively adopts the SQP optimization method to iteratively optimize the objective function and studies the design and optimization method of the gradient coil. It can be seen from the numerical simulation results that compared with the standard rectangular Helmholtz gradient coil and circular Helmholtz gradient coil, the optimized gradient coil adopts the structure form of rectangular and circular coils, which greatly improves the gradient uniformity. The gradient deviation value is reduced from 35% and 43% to 7%, respectively. The optimization method can be used for the simulation and design of high uniformity field gradient coil to guide engineering practice.

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