

A design method of biplanar coils for producing spatial nonlinear field

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This paper presents a design method for a biplanar coil to achieve a spatially nonlinear magnetic field (SNMF) distribution. The higher-order components of the magnetic field produced by the biplanar coil can increase the discrepancy between simulated and actual values, thereby reducing magnetic field uniformity in the target area. To address this problem, the Taylor expansion method (TEM) is integrated into the traditional target field method (TFM), and an improved particle swarm optimization algorithm is employed to determine the coil parameters and shape. The simulation results show that the magnetic field deviation generated by the asymmetric coils in the -200 mm to 200 mm range is -2.32%~1.08% compared with the preset field, which demonstrates that the proposed method effectively generates the desired magnetic field distribution.

Index Terms—Biplanar coil, spatially nonlinear magnetic field (SNMF), Taylor expansion method (TEM), target field method (TFM).

I. INTRODUCTION

In recent decades, precise magnetic field regulation has found extensive applications in cancer treatment [1], medical applications [2] and various industrial processes [3]. This technology can accurately control magnetically sensitive materials' attitude, speed, and position, making it valuable for various domains such as magnetic drug delivery and satellite attitude control. Compared to other control methods, effective magnetic field control offers significant advantages, including rapid response, non-contact operation, non-destructive effects, easy controllability, enhanced flexibility and robustness [4]. As research progresses, achieving high-precision control of inhomogeneous magnetic fields becomes increasingly critical. For instance, spatial nonlinear magnetic fields (SNMFs) can facilitate the reorientation of magnetically sensitive propellants, thereby enhancing the controllability of fluid systems in space environments.

Magnetic field generation methods mainly include permanent magnets and energized coils. Compared to permanent magnets, energized coils offer variable and controllable magnetic fields by adjusting the current, making them more suitable for high-precision applications. Traditional coil designs, such as Helmholtz, Merritt, and saddle, primarily produce uniform or gradient fields along the central axis. To enhance their applicability, biplanar coils tailored for specific magnetic field distributions have been developed. The desired magnetic field is usually achieved through the target field method (TFM) in biplanar coil design. However, the complexity of constructing and solving SNMF makes related coil designs rarely considered.

Based on the considerations mentioned, this digest presents a novel method for designing biplanar coils to generate specific SNMF. Combining the two coils' magnetic field expressions can reconstruct an overdetermined equation to achieve varied field distributions. The paper introduces the Taylor expansion method (TEM) into the TFM to minimize actual magnetic field errors. This approach effectively reduces deviations by

suppressing higher-order magnetic field components. Preliminary finite element analysis (FEA) results for a pair of B_x coils designed using this method are also discussed.

II. PRINCIPLE

Fig 1 depicts a schematic drawing of biplanar coils. One pair of coils embedded in two square plates is symmetrically placed. Each plate has a side length of 1700 mm and is separated by a distance of 1400 mm. The target area is at the center of the two plates, along a central line with a length of 400 mm. A Cartesian coordinate system is established with the center point as the origin. The target magnetic field distribution is set as exponential:

$$B_{target} = 77.134 \times \exp\left(\frac{7}{8}z\right)$$

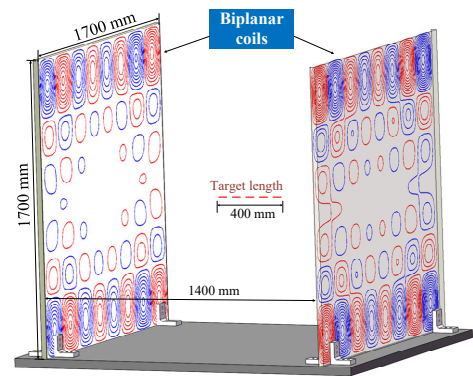


Fig. 1. Schematic drawing of the B_x biplanar coil.

Firstly, the magnetic field generated by the original coil at the point (x, y, z) is denoted as $B_{(0,0,0)}(x, y, z)$. According to Biot-Savart law, the expression for the magnetic field within the target region can be written as [5]:

$$B_x(x, y, z) = \frac{\mu_0}{2\pi} \iint \frac{\mathbf{J} \times \mathbf{r}}{\|\mathbf{r} - \mathbf{r}'\|^3} dA' = \frac{\mu_0}{2\pi} \iint \frac{J_y(x, y) \cdot (z - z')}{\|\mathbf{r} - \mathbf{r}'\|^3} dA'$$

$$J_y(x, y) = \sum_{m=1}^M \sum_{n=1}^N \frac{P_{mn} \pi m}{L} \cos\left(\frac{\pi m x}{L}\right) \cos\left[\frac{\pi}{2}(2n-1)\frac{y}{L}\right]$$

where μ_0 represents the vacuum permeability. $\mathbf{J}$ represents the current density on the plane, $\mathbf{r}$ and $\mathbf{r}'$ represent the field point and source point, and $d\mathcal{A}'$ represents the surface area integration element of the current density. According to the TFM, the magnetic flux density B_x can be expressed as:

$$B_x(x, y, z) = B_{target}$$

Next, the TEM is introduced for further constraints to minimize the impact of higher-order components in the expression on the actual magnetic field[6]. As the stream function's symmetry, the magnetic field's first derivative is zero. Therefore, constraining the second derivative of the magnetic field is necessary because the second-order derivative contributes the most to the total deviation of the desired field:

$$\frac{\partial^2 B_x}{(\partial x^2, \partial y^2, \partial z^2)} = 0$$

To address the PSO optimization algorithm's tendency for premature convergence and oscillation near the global optimum of the current density coefficient P_{mn} , a linear decreasing inertia weight method is introduced finally, which allows the inertia weight coefficient w to change during the optimization process:

$$w = w_{\max} - \frac{t \times (w_{\max} - w_{\min})}{t_{\max}}$$

where $w_{\max}$ and $w_{\min}$ represent the weight coefficient's upper and lower bound, respectively. The inertia weight of the particles decreases as the optimization process progresses. Compared to the traditional PSO algorithm, the new approach theoretically enhances the optimization of coil parameters and reduces the deviation of the actual magnetic field. The coil windings obtained by this method are shown in Fig 2. The uniformity of the magnetic field ΔB at the point (x, y, z) is defined as:

$$\Delta B(x, y, z) = \frac{B(x, y, z)}{B_{target}} - 1$$

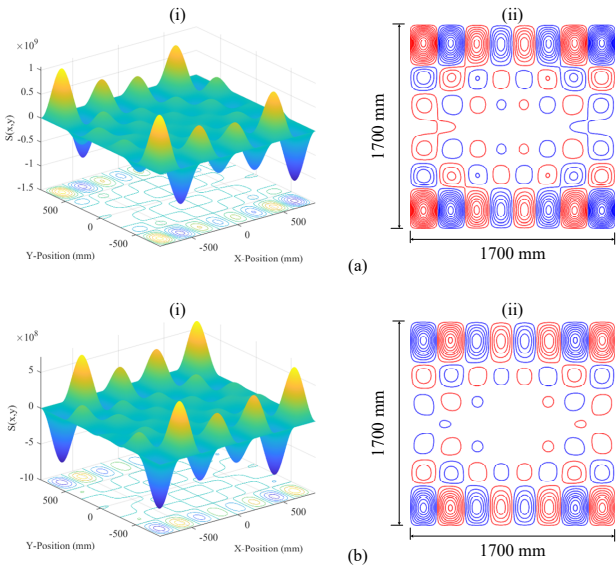


Fig. 2. (i)Stream function S and (ii) coil windings of the pair (a) (b) of B_x coils.

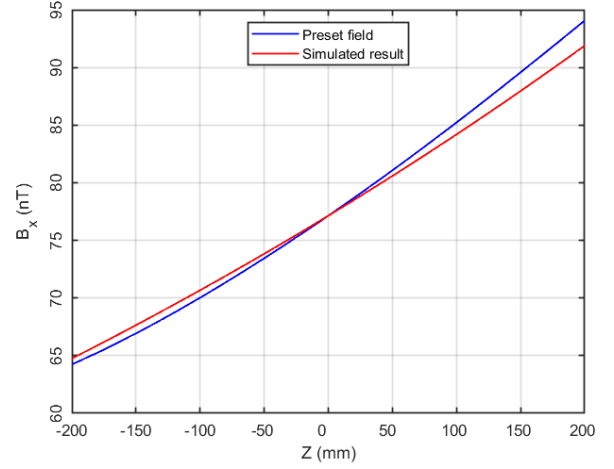


Fig. 3. Comparison between preset field and simulated result of B_x coil in the target region.

III. CONCLUSION

The effectiveness of the proposed method is validated using FEA (COMSOL Multiphysics 5.5 software). The simulation focuses exclusively on the self-generated magnetic field of the coil, evaluating its deviation from the preset field distribution in the target region, and the results are provided in Fig 3. The results indicate that the deviation ΔB_x of the designed B_x coil in the target area ranges from -2.32% to 1.08% after incorporating the higher-order component of the TEM confinement magnetic field and enhancing the optimization performance. This demonstrates that the proposed method effectively generates the desired magnetic field distribution. Additionally, the improved optimization algorithm is well-suited for the parameter optimization process.

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