Design and research of electromagnetic generator based on Helmholtz coil

Jinshan Chen¹, Yongkang Shi*¹
¹School of Mechanical Engineering, Xinjiang University, Urumqi, Xinjiang Province, 830017, China
*Corresponding author’s e-mail: sunwenxj@sina.cn

Abstract. According to the technical requirements of electromagnetic-eddy current spin-off test for space targets, an electromagnetic generator is designed based on the working principle of the Helmholtz coil, the utility model is composed of a pair of square coils of the same structural size and turns of the coils. The magnetic field generated by the electromagnetic generator is simulated and analyzed by using the Maxwell electromagnetic simulation software, and the distribution of the magnetic field on the X axis, Z axis and the surface of the square coil is observed, the Tesla Meter was used to measure the magnetic field at 27 locations in the central region of the electromagnetic generator. The results show that the uniform magnetic field range, the magnetic induction and the uniformity of the magnetic field produced by the electromagnetic generator can meet the requirements of the electromagnetic eddy current damping test.

1. Introduction
The electromagnetic eddy current racemization technology of space target has the physical basic conditions for realization. It is a racemization means with obvious advantages. Foreign countries already have a practical technical basis. In China, the research on electromagnetic eddy current racemization of failed spacecraft is rarely verified by experiments except the derivation and Simulation of mathematical model [1].. Due to the huge cost of space experiment, a large number of ground experiments are needed to ensure the normal operation of various equipment in space experiment and achieve the required performance indicators. According to the requirements of electromagnetic eddy current racemization test of space target, the test needs to produce a uniform magnetic field of sufficient size to meet the electromagnetic eddy current racemization process.

Kun Liu [2], constructed a mathematical model of a square Helmholtz coil, derived the correspondence between the output current and the magnitude of the generated magnetic field, and simulated a stable and constant magnetic field using a constant current source and a magnetometer. Sugai [3]. has conducted ground tests of the deconfliction brake and designed two miniature electromagnetic coils with a diameter of about 100mm, which produce a small magnetic field and can only brake the target at close range. Chang-Hua Dong [4]. concluded that square coils have the lowest power, higher uniformity, and easier assembly when the central magnetic induction strength, effective internal holding space, and incoming AC current are the same. Ronald [5]. used Biot-Savart law to determine the size and direction of the magnetic field around a square Helmholtz coil, generating a 200 μT magnetic field that was used to calibrate sensors mounted on satellites. Natalia [6]. designed a ground test platform to verify the electromagnetic-eddy current model. The superconducting coil is used to generate a super-strong magnetic field, but it needs a complicated control system and cooling.
circulation system. Jing-Wen Zhang [7]. introduced a three-axis square electromagnetic field generator used in electromagnetic biology experiment, deduced the expression of magnetic induction intensity of three-axis square Helmholtz coil, and designed a complete set of Helmholtz coil magnetic field generator. Zhao-Hui Hu [8]. proposed a method to calculate the parameters of cylindrical coil group with any number of coils, which is used to design the coil group generating high uniformity magnetic field. Jing Gao [9]. deduced the spatial magnetic field distribution expression of Helmholtz coil, simulated the magnetic field distribution of Helmholtz coil with radius r, and obtained that the magnetic field distribution is relatively uniform in (-R/2, R/2) region in XOY plane. Qun-Yi Zhou [10]. explained the analytical formula of the two components of the magnetic field of the Helmholtz coil, plotted the range of the magnetic field uniform region under critical conditions, and explained the influence of the distance between the two rings on the shape of the magnetic field uniform region. Xin-Yue Gao [11]. establishes the simulation model of Helmholtz coil through ANSYS software platform, and obtains the magnetic field distribution of Helmholtz coil with different dimensions through simulation analysis.

To sum up, the design method and design process of the above coils are summarized to avoid the problem of too small magnetic field. According to the technical requirements of electromagnetic eddy current racemization test of space target, an electromagnetic generator is designed in this paper. Use Maxwell electromagnetic simulation software to simulate and analyze the magnetic field generated by the electromagnetic generator, determine the structural parameters of the electromagnetic generator, and use Tesla meter to measure the magnetic field in the central area of the electromagnetic generator. The uniform magnetic field range, magnetic induction intensity and magnetic field uniformity produced by the electromagnetic generator can meet the requirements of electromagnetic eddy current racemization test.

2. Technical specification of electromagnetic field
According to the technical requirements of electromagnetic-eddy current spin-off test for space targets, the electromagnetic generator should be able to generate a magnetic field which can meet the needs of spin-off braking and is uniform in the central region. Uniform magnetic field strength: 14mT. Uniform magnetic field: 140mm×140mm×140mm. Uniformity of uniform magnetic field: less than 1%.

3. Square Helmholtz coil
3.1. Axial magnetic field
The Helmholtz coil consists of a pair of identical, coaxial, parallel coils with the same load current, a square Helmholtz coil is a pair of identical, coaxial, parallel, square current carrying coils with n turns of coil. As shown in Figure 1, this is a diagram of a square Helmholtz coil.

![Figure 1. A pair of coaxial square Helmholtz coils](image)

The size of the magnetic induction produced at any point P (0,0,Z) on the central axis is

\[
B = \frac{2\mu_0 I^2}{\pi} \left\{ \frac{1}{(L^2 + (d + z)^2)^{3/2}} + \frac{1}{(L^2 + (d - z)^2)^{3/2}} \right\}
\]
In the formula: $2L$ is the length of the coil side, $2d$ is the center distance of a pair of square coils, $d$ and $L$ satisfy the relation formula $d = 0.5445L$ [12], $I$ is the input current of the coil, $\mu_0$ is the vacuum permeability, $\mu_0 = 4\pi \times 10^{-7} \text{N} / \text{A}^2$, $z$ is the distance from P to O on the central axis; $Z$ is the magnetic induction direction.

3.2. 3D modeling

The electromagnetic generator uses a pair of square coils with the same number of turns, side length, height, and thickness, placed in parallel with each other, to form a square Helmholtz coil. The coil dimensions are as follows: the coil is 640 mm in length and width, the thickness of the coil is 35 mm, the height of the single coil is 42 mm, and the central distance between the two coils is 322 mm. The 3D model of the square Helmholtz coil is shown in Figure 2. The square Helmholtz coil is made of copper, and its permeability is $\mu = \mu_0 = 4\pi \times 10^{-7} \text{H/m}$.

Since the square Helmholtz coil model is relatively simple, the automatic mesh generation method is used, and the finite element analysis model after the mesh generation is shown in Figure 3.

4. Simulation analysis

When the current $I = 80 \text{A}$ is inputted to the electromagnetic generator, the magnetic field of the square Helmholtz coil in the electromagnetic generator is analyzed by the Maxwell electromagnetic simulation software, and the magnetic field distribution at different positions of the coil can be obtained, through the different position magnetic field to observe whether the coil meets the technical specifications.

As shown in Figure 4, the magnetic field distribution on the X axis of a square Helmholtz coil is shown in the direction of Path 1 to further observe the magnetic induction distribution on the X axis. The magnetic induction of Path 1 is shown in Figure 5.

As can be seen from Figure 4 and Figure 5, the electromagnetic distribution in the X axis direction of the square Helmholtz coil is fairly uniform, reaching 14 mT in the -122 mm – 136 mm region of the
X axis, and the electromagnetic field of the square magnetic induction reaches 14 mT in the X axis, and the uniformity is less than 1%.

As shown in Figure 6, the magnetic field distribution on the Z axis of the square Helmholtz coil is shown in the direction of Path 2, and the magnetic induction distribution on the Z axis is further observed. The magnetic induction of Path 2 is shown in Figure 7.

As can be seen in Figure 6 and Figure 7, the electromagnetic distribution in the z axis of the square Helmholtz coil is fairly uniform, reaching 14 mT in the -73 mm ~ 91 mm magnetic induction of the Z axis, and the uniformity is less than 1%.

Path 3 is 150 mm from the coil center (170 mm from the coil surface) and parallel to the z axis, and Path 4 is 200 mm from the coil center (120 mm from the coil surface) and parallel to the Z axis, Path 5 is 250 mm from the center of the coil (70 mm from the surface of the coil) and parallel to the Z axis. As shown in Figure 8, this is a map of the magnetic field distribution over the square Helmholtz coil Path 3, Path 4, and Path 5. As shown in Figure 9, the magnetic induction of Path 3, Path 4, and Path 5.

As can be seen from Figure 8 and Figure 9, the magnetic field at both ends of the coil gradually increases in size and magnitude as compared with that at Path 2, in the region gradually approaching the surface of the magnetic induction, the magnetic induction on Path 3, Path 4, and Path 5 show a hump pattern. Comparing Figure 7 and Figure 9, it can be seen that the closer the magnetic field is to the central region, the more uniform the magnetic field distribution is, especially in the Z axis direction.

From the results of the simulation analysis in Figure 4-Figure 9, it can be seen that the magnetic field distribution in the central region is fairly uniform except for the inner edge of the coil. The uniform magnetic field can reach the magnetic field intensity can reach 14mT, the uniformity is less than 1%, so the design parameters of the electromagnetic generator can meet the test requirements.
5. Experimental verification

According to the simulation results and the requirements of the electromagnetic-eddy current de-whirl test of the space target, the parameters of the designed electromagnetic generator are as follows.

(1) The square Helmholtz coil of the electromagnetic generator consists of a pair of square coils with the same turns, side length, height and thickness, which are placed parallel to each other.

(2) The shape of single coil is 640mm in length and width, 35mm in thickness and 42mm in height.

(3) 70 turns of copper insulated enameled wire selected by square coil.

(4) The central distance of the two square coils is 322mm.

(5) The uniform magnetic field area of the electromagnetic generator is 14mm x 14mm x 14mm.

(6) The uniform magnetic field magnetic induction of the electromagnetic generator is 14mT.

(7) The uniformity of the uniform magnetic field of the electromagnetic generator is less than 1%.

(8) The input current of the electromagnetic generator is 80A.

After the completion of the electromagnetic generator according to the above parameters, as shown in Figure 10, 27 position points within the central area of 140mm x 140mm x 140mm inside the square Helmholtz coil of the electromagnetic generator were selected for the measurement of magnetic induction intensity, and the TD8650 Tesla Meter was used to test the above points with a resolution of 0.001mT and an accuracy of ±0.5%.. The electromagnetic generator test connection diagram is shown in Figure 11, the coil is connected to 80A current, and the coordinate values of each point and the measured magnetic induction intensity are shown in Table 1.

![Figure 10. Schematic diagram of magnetic field test points](image1)

![Figure 11. Test connection diagram of electromagnetic generator](image2)

| Serial number | Coordinate value | Magnetic induction | Serial number | Coordinate value | Magnetic induction |
|---------------|------------------|--------------------|---------------|------------------|--------------------|
| 1             | (-70,-70,70)     | 14.227mT           | 15            | (70,0,0)         | 14.107mT           |
| 2             | (0,-70,70)       | 14.106mT           | 16            | (-70,70,0)       | 14.093mT           |
| 3             | (-70,70,70)      | 14.284mT           | 17            | (0,70,0)         | 14.096mT           |
| 4             | (-70,0,70)       | 14.123mT           | 18            | (70,70,0)        | 14.070mT           |
| 5             | (0,0,70)         | 14.085mT           | 19            | (-70,-70,-70)    | 14.160mT           |
| 6             | (70,0,70)        | 14.055mT           | 20            | (0,-70,-70)      | 14.087mT           |
| 7             | (-70,70,70)      | 14.183mT           | 21            | (-70,-70,0)      | 14.191mT           |
| 8             | (0,70,70)        | 14.081mT           | 22            | (-70,0,-70)      | 14.071mT           |
| 9             | (70,70,70)       | 14.156mT           | 23            | (0,0,-70)        | 14.094mT           |
| 10            | (-70,-70,0)      | 14.074mT           | 24            | (70,-70,0)       | 14.102mT           |
| 11            | (0,-70,0)        | 14.094mT           | 25            | (-70,70,-70)     | 14.160mT           |
| 12            | (-70,70,0)       | 14.123mT           | 26            | (0,70,-70)       | 14.116mT           |
| 13            | (-70,0,0)        | 14.077mT           | 27            | (70,70,-70)      | 14.184mT           |
| 14            | (0,0,0)          | 14.061mT           |               |                  |                    |
From the measurement results of the above 27 test points, it can be seen that the simulation results of the electromagnetic generator internal magnetic induction are basically consistent with those of the Maxwell electromagnetic simulation software, and the distribution of the electromagnetic generator is fairly uniform in the central area of $140\text{mm} \times 140\text{mm} \times 140\text{mm}$, the magnetic induction reaches 14 mT, and the uniformity is less than 1%, which can meet the needs of electromagnetic eddy current spin test for space targets.

6. Conclusion
(1) According to the requirements of electromagnetic eddy current racemization test of space target, an electromagnetic generator is designed based on the working principle of Helmholtz coil. The square Helmholtz coil of the electromagnetic generator is composed of a pair of coaxial parallel square coils with the same number of turns, side length, height and thickness. The overall length and width of a single coil are 640mm, the thickness is 35mm and the height is 42mm. The center distance of the two coils is 322mm. The copper insulated enameled wire selected by the coil is wound with a total of 70 turns. The input current of the coil is 80A. The uniform magnetic field area is $140\text{mm} \times 140\text{mm} \times 140\text{mm}$, the magnetic induction intensity in the uniform magnetic field area is 14mT, and the magnetic field uniformity in the uniform magnetic field area is less than 1%.

(2) A three-dimensional model of the square Helmholtz coil is established, and the magnetic field of the coil is simulated and analyzed by using Maxwell, the results show that the uniform magnetic field region, the magnetic induction and the uniformity of the magnetic field distribution in the coil can meet the requirements of the test.

(3) According to the results of simulation and analysis, the structure parameters of the electromagnetic generator are determined. The actual test results show that the magnetic field distribution of the 27 test points in the $140\text{mm} \times 140\text{mm} \times 140\text{mm}$ region is uniform, and the magnetic induction can reach 14 mT, and the uniformity is less than 1%, which can meet the needs of electromagnetic-eddy current de-swirling test of space target. The next step will be the electromagnetic-eddy current de-rotating ground test.

Reference
[1] Shi, Y K., Yang, L P., Zhu, Y W., og Chu F D. (2018) Modeling and Simulation of Superconducting Eddy Brake Concept for Space Tumbling Object. Journal of Astronautics, 39(10):1089-1096.
[2] Liu K., Zhang S Y., og Gu W. (2012) Analysis on magnetic field homogeneity of magnetic system based on square Helmholtz coils. Modern Electronics Technique, 35(7):190-194.
[3] Sugai, F., Abiko, S., Tsujita, T., Jiang, X. og Uchiyama, M. (2013) Detumbling an uncontrolled satellite with contactless force by using an eddy current brake. I 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 783-788.
[4] Dong C H., og Zhang Y S. (2016) Comparative study of square and circular Helmholtz coils in clinical application. Mechanical & Electrical Technology, (03):2-5.
[5] Hurtado-Velasco, R. og Gonzalez-Llorente, J. (2016) Simulation of the magnetic field generated by square shape helmholtz coils. Applied Mathematical Modelling, 40(23-24): 9835-9847.
[6] Gomez, N. O. (2017). Eddy currents applied to space debris objects. 92-112.
[7] Zhang J W., Liu Y Q., Wu R B., Sun Y T., og Du B T. (2018) A Tri-axial Square Helmholtz Coil for Generating Magnetic Field. Electrical Engineering Materials (02): 43-46.
[8] Hu, Z H., Mu W W., Wu W F., og Zhou B Q. (2018) Design method of cylindrical coil systems for generating uniform magnetic field. Journal of Beijing University of Aeronautics and Astronautics, 44(3): 454-461.
[9] Gao J., Sun X., og Liu J W. (2018) Research on the Spatial Distribution of Helmholtz Coil Magnetic Field. Bulletin of Science and Technology, 34(07): 34-37.
[10] Zhou Q Y., Mo Y F., Zhou L L., og Hou Z Y. (2021) Research and Visualization of the Uniform Range of the Helmholtz Coil's Magnetic Field. Journal of Changsha University, 35(05): 13-
17+28.

[11] Gao X Y., Zhao Y H., LI D., og Shen Y. (2021) Experimental research on magnetic field distribution of Helmholtz coil based on ANSYS. Experimental Technology and Management, 38(05): 175-179+186.

[12] Gu X R., (2000) The evaluation of the optimum space of square Helmholtz coil. Geophysical and Geochemical Exploration, 24(5).