Magnetic Field Analysis of Rectangular Current-carrying Coil Based on ANSOFT Maxwell 3D Simulation

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Abstract. In this work, in order to analyse the magnetic field of rectangular current-carrying coil, a simulation with the magnetostatic function of the ANSOFT Maxell 3D software has been carried out. The characteristics of the magnetic field distribution have been analysed based on the results of simulation. In addition, an experiment aimed to measure the magnetic induction intensity at a point on the central axis of the rectangular coil has been designed to verify the simulation results. The results show that the error between the simulation results and the actual measurement is 1.24%, which proved the accuracy of the simulation.

1. Introduction
Rectangular current-carrying coil is widely used in scientific research and industrial production. Hence it is significant to study the magnetic field distribution of rectangular coil. However, most of the research is focused on the circular coil [1-3]. Although there is some research related to the rectangular coil [4, 5], it lacks a method that is both practical and accurate. ANSOFT Maxwell 3D is a high-performance 3D electromagnetic design software based on the Finite element method (FEM). It can give us the magnetic induction intensity date in the area we are interested in and visualize the result data.

2. Finite element model
The coil used in the research is formed by uniformly winding 50 turns of enameled wire with a wire diameter of 0.1mm on the 4mm×2mm and 10mm×2mm surface of a 4mm×10mm×2mm rectangle. When the coil is energized, the coil generates magnetic field.

For ease of description, a Cartesian coordinate system is established, as shown in figure 1. Due to the uniform and dense winding of the enameled wire, the coil can be simplified into a pure copper body with a 4mm×10mm×2mm rectangular frame extending outward by 0.2mm. And the environment around the coil is simplified to be a 4000% air region. The main material parameters are shown in Table 1. Since the coil enameled wire current in the study is 35.28mA and the turn number is 50, the ampere turns are set to 1764mA-turn in software. Meshing and boundary conditions retain default settings.
Table 1. Main material parameters

|                | Relative Permeability | Bulk Conductivity (siemens /m) |
|----------------|-----------------------|---------------------------------|
| Copper         | 0.999991              | 58000000                        |
| Air            | 1.000004              | 0                               |

3. Simulation results analyses

Importing the above model in Maxwell 3D software to solve, and then the result data is generated. With the Maxwell 3D post-processing module, the iso-surface magnetic induction intensity of the rectangular coil is plotted in figure 2.

Figure 2. The iso-surface magnetic induction intensity of the rectangular coil cut from the y=5 plane.

It can be seen from figure 2:
- Points with large magnetic induction intensity are concentrated near the coil.
- The magnetic induction intensity in the coil is larger than that outside the coil, and as the distance from the coil increases, the magnetic induction intensity gradually decreases.
- The uniformity of the magnetic induction intensity generated by the rectangular current-carrying coil is poor, but has a good symmetry.

3.1. Magnetic induction intensity distribution on the section perpendicular to x-axis
The Maxwell 3D post-processing module is used to generate the magnetic induction intensity vector nephogram on the x=1, x=1.8, x=2.6 and x=3.4 section of the coil. The results are shown in figure 3 (a), (b), (c), (d) respectively.

![Nephogram for different sections of the coil](image)

Figure 3. Magnetic induction intensity vector nephogram on the x=1, x=1.8, x=2.6 and x=3.4 section of the coil.

It can be seen from figure 3:

- The magnetic induction intensity gradually increases from the center of the section to the periphery, and is strongest at the four corners. When the section gradually moves in the positive direction of x-axis, the points with stronger magnetic induction gradually move toward the center of the section. Finally, the magnetic induction at the four corners becomes the weakest.
- When the section gradually moves in the positive direction of x-axis, the magnetic induction intensity gradually decreases in general.
- The magnetic induction intensity distribution is symmetric about the center of the section, which is consistent with the symmetry of the rectangle.

3.2. Magnetic induction intensity distribution on the section parallel to x-axis

The Maxwell 3D post-processing module is used to generate the magnetic induction intensity vector nephogram on the y=2, y=5, z=0 and 2y+5z-20=0 section of the coil. The results are shown in figure 4 (a), (b), (c), (d) respectively.
It can be seen from figure 4:

- The characteristics of magnetic induction intensity distribution on the x-axis parallel sections at different locations are similar. The magnetic induction intensity near the coil area is strong and gradually decreases outward.
- The magnetic induction is more uniform in the area near the section center.
- Similar to the section perpendicular to x-axis, the magnetic induction intensity distribution on the section parallel to x-axis is also symmetric about the center of the section.

3.3. Magnetic induction intensity distribution on the central axis of the coil

Since the applications of most rectangular current-carrying coils are concerned with the magnetic field on the central axis of the coil, the magnetic induction intensity distribution on the central axis is separately described here. The central axis of the coil refers to the intersection of the plane y=5 and plane z=2. Take the line segment with the x-coordinate of the center axis from -14mm to 16mm, and use the Maxwell 3D post-processing module to obtain the magnetic induction intensity corresponding to the points on the line segment. The corresponding relationship between the x-coordinate and the magnetic induction intensity is shown in figure 5. It can be seen from the figure 5 that the maximum magnetic induction intensity is located at the center of the line segment, and as the distance between the two sides increases, the magnetic induction intensity rapidly decreases.
4. Experimental validation

To verify the numerical accuracy of the Maxwell 3D simulation results, we use a ring laser magnetic field sensor to measure the magnetic induction intensity at a point on the central axis. The ring laser magnetic field sensor utilizes the Faraday bias to measure the magnetic induction intensity [6]. The relationship between the Faraday bias and the magnetic induction intensity is

\[ \nu_f = \frac{cVl}{\pi \langle L \rangle} B \]

where \( \nu_f \) is the Faraday bias, \( B \) is the magnetic induction intensity, \( c \) is the speed of light, \( V \) and \( l \) are the Verdet constant and length of Faraday cell, \( \langle L \rangle \) is the optical length of the ring cavity. In this experiment, Faraday bias element uses 2mm long quartz glass with \( V = 0.06166832 \text{rad} \cdot T^{-1} \cdot mm^{-1} \), optical length of the ring cavity is 285.1088789mm, so the calculated sensitivity is 0.2426uT based on Eq.(1).

For the ease of experiment, we made a coil set consisting of four rectangular coils mentioned above. The structure of the coil set is shown in figure 6, where \( B_0 \) is the magnetic induction intensity at the center of the coil set, and \( B_1 \) is the magnetic induction intensity generated by a single rectangular coil. According to vector composition law, \( B_0 = 2\sqrt{3}B_1 \).

The experiment is shown in the figure 7. When the current switch is turned on, the Faraday bias decreases \( \Delta \nu_1 = 77.4912 \text{Hz} \) which is generated by the magnetic field of the coil set. Then turn off the switch, the Faraday bias increases \( \Delta \nu_2 = 78.2776 \text{Hz} \). Considering about the temperature draft of the Faraday bias, the average of \( \Delta \nu_1 \) and \( \Delta \nu_2 \) is taken into calculation. The results show that the magnetic induction intensity of a single rectangular current-carrying coil is 5.4544607uT at point A. The simulation result data at the same position is 5.386567uT, and the error is about 1.24% compared with the experimental result. Considering about the error in the process of coil winding and installation, the accuracy of the FEM based on ANSOFT Maxwell 3D is acceptable.
5. Conclusion

In this paper, the magnetic field of the rectangular current-carrying coil is simulated based on ANSOFT Maxwell 3D software, and the accuracy of the simulation is proved by an experiment with ring laser magnetic field sensor. The above research can provide reference for practical application. In addition, by modifying the FEM model, the FEM method based on ANSOFT Maxwell 3D can be used in other complex structures.

References

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