Magnetic field simulation and shimming analysis of 3.0T superconducting MRI system

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Abstract. 3.0T superconducting magnetic resonance imaging (MRI) system has become the mainstream of modern clinical MRI system because of its high field intensity and high degree of uniformity and stability. It has broad prospects in scientific research and other fields. We analyze the principle of magnet designing in this paper. We also perform the magnetic field simulation and shimming analysis of the first 3.0T/850 superconducting MRI system in the world using the Ansoft Maxwell simulation software. We guide the production and optimization of the prototype based on the results of simulation analysis. Thus the magnetic field strength, magnetic field uniformity and magnetic field stability of the prototype is guided to achieve the expected target.

1. Introduction
In recent years, MRI has become an important non-invasive tomography technique, which plays an increasingly important role in clinical diagnosis and treatment. High field MRI system has a great advantage in SNR, resolution and scanning time. So the detection rate of microstructure and minimal lesion of high field MRI system is significantly better than that in middle and low MRI system. It can also shorten the patient's examination time and carry out the research of spectrum and functional imaging. And high field MRI system has become the mainstream of the current market [1].

The first cross-sectional magnetic resonance images of human fingers were taken by Mansfield and Maudsley in 1973 and they shared the 2003 Nobel Prize in Physiology or Medicine [2]. The first commercial magnetic resonance scanner in Europe was built in 1983 at the Radiology Diagnostics School at Manchester Medical University. The magnetic field strength of most MRI systems on the market was less than or equal to 0.6T since they were applied to medical practice in the 1970s. In China, the application of superconducting technology began in the 1960s and 1970s. The first 1.5T MRI system appeared in the early 1980s and became the dominant magnetic field strength in clinical high-quality magnetic resonance imaging systems in the late 1980s. In the 80s and 90s, China Kejian Co. Ltd developed the first 0.5T superconducting magnetic resonance magnet [3-6].
The 3.0T/850 superconducting MRI molecular imaging system meets the high quality imaging requirements. The magnetic induction intensity of its magnet center is stronger or equal to 3.0T. The magnetic field uniformity of its 45cm spherical imaging region after shimming is less than 10ppm, of which the magnetic field stability is less than 0.1ppm/h. And its effective magnetic field keeps longer, which can reduce maintenance costs and maintenance frequency and ensure the definition of imaging. It can conduct research on spectroscopy, molecular imaging and functional imaging because it has obvious advantages in SNR and DPI. The 3.0T/850 superconducting MRI molecular imaging system is an advanced dual platform of clinical and research [7].

2. Theory
In this paper, we mainly studied designing principles of superconducting magnet and principles of magnetic field shimming.

2.1. Principle of magnet designing
In this paper, the superconducting magnet is made of a number of hollow cylindrical coils, which is designed according to the principle of the sixth-order coil designing [8]. The magnetic field generated by the superconducting magnet is treated as the superposition of magnetic fields generated by several hollow cylindrical coils. Fig. 1 shows cross section diagram of the hollow cylindrical coil. The current in the superconductor is evenly distributed when the magnetic field strength is much higher than the critical magnetic field of the superconductor. The formula of field strength distribution of hollow cylindrical coil with uniform current distribution is shown in (1). Among them, \( j \) is the current density (\( A/cm^2 \)) and \( \lambda \) is the filling factor. The materials of superconducting wire are used in the commonly used niobium titanium alloy.

![Figure 1. Simplified schematic diagram of hollow cylindrical coil.](image-url)
2.2. Magnetic field simulation and shimming analysis

The design of the main magnet system requires a highly uniform and highly stable magnetic field. It must be solved numerically according to the theory of electromagnetic field with reliable and convenient computer software. We use Ansoft Maxwell simulation software to simulate the magnetic field distribution of the superconducting magnet in order to provide a scientific basis for the design and optimization of the magnet.

The magnetic field of superconducting magnet can be influenced by its design, manufacturing, installation environment and other factors. Thus the uniformity of the main magnetic field needs to be adjusted to achieve a certain degree to obtain high quality magnetic resonance images. The non-source shimming technology distribute the magnetic field evenly by optimizing the distribution of a series of shimming pieces (magnetic material, usually electrical steel) [9]. In practice, the number of shimming pieces should be controlled at a minimum when shimming requirements are met. Because the presence of shimming pieces may introduce thermal stability and eddy current problems. In this paper, we calculate the shimming radius using the extreme location method to regulate the position of shimming pieces. To avoid repeated correction, successive approximation is presented to calculate the number of shimming pieces [10].

3. Simulation and experimental results

The simulation model of this superconducting magnet is established using Ansoft Maxwell simulation software. We get the distribution curve of magnetic strength along axial direction of the magnet (as shown in Fig. 2) and the magnetic field distribution in the 45cm spherical imaging region (as shown in Fig. 3).

\[
B_\ell (\alpha, \beta) = \frac{2\pi \mu_0}{S} \sum_{m} M_m \left( \frac{\ell - \alpha}{R_i} \right)^m P_m \left( \frac{\ell - \beta}{R_i} \right)^m + \ldots
\]

\[
\beta = b \frac{R_i}{R} = \frac{R_i}{R}
\]

\[
C_1 = \frac{1}{1 + \beta^2}, \quad C_2 = \frac{\beta^2}{1 + \beta^2}, \quad C_3 = \frac{\alpha^2}{\alpha + \beta}, \quad C_4 = \frac{\beta^2}{\alpha + \beta}
\]

\[
M_n = \beta \frac{\alpha \ln \left( \frac{\sqrt{1 + \beta^2}}{1 + \beta^2} \right)}{1 + \sqrt{1 + \beta^2}}, \quad M_s = \frac{1}{2} \frac{\alpha \beta \left( C_{11}^{(n)} - C_{11}^{(m)} \right)}{1 + \beta^2}
\]

\[
M_{s1} = \frac{1}{12} \alpha^2 \beta^2 \left[ C_{11}^{(n)}\left( \frac{1}{2} C_{11} + \frac{15}{2} C_{1} \right) - C_{11}^{(n)}\left( \frac{1}{2} C_{11} + \frac{15}{2} C_{1} \right) \right]
\]

\[
M_{s2} = \frac{1}{30} \alpha^2 \beta^2 \left[ C_{11}^{(n)}\left( \frac{1}{2} C_{11} + \frac{15}{2} C_{1} \right) - C_{11}^{(n)}\left( \frac{1}{2} C_{11} + \frac{15}{2} C_{1} \right) \right]
\]

\[
\cos \theta = \mu, \quad P_m = \frac{1}{2} (3\mu^2 - 1), \quad P_s = \frac{1}{8} (15\mu^4 - 30\mu^2 + 8)
\]

\[
P_s = \frac{1}{16} (231\mu^8 - 315\mu^6 + 105\mu^4 - 5)
\]
Figure 2. Distribution curve of magnetic strength along axial direction.

Figure 3. Magnetic field distribution in the 45cm spherical imaging region.

We add shimming pieces in the original magnet model through the analysis of simulation results. Then we calculate and optimize the location and quantity of shimming pieces. We also get the distribution curve of magnetic strength along axial direction (as shown in Fig. 4) and the magnetic field distribution (as shown in Fig. 5) after shimming.

Figure 4. Distribution curve of magnetic strength along axial direction after shimming.

Figure 5. Distribution curve of magnetic strength along axial direction after shimming.
According to the simulation results, the prototype is designed and optimized. The superconducting magnet of medical 3.0T/850 MRI system is excited successfully by Weifang Xinli Superconducting Magnetic Technology Co., Ltd on June 15, 2017. Then we perform a series of experiments. The magnetic field strength, magnetic field uniformity and magnetic field stability of the prototype achieve the expected target.

4. Conclusions
In this paper, we analyze the principle of magnet designing. In order to provide a scientific basis for the design and optimization of magnets. We perform the magnetic field simulation and shimming analysis of the 3.0T/850 superconducting MRI system using the Ansoft Maxwell simulation software. The prototype is designed and optimized according to the simulation results. Through testing the prototype as shown in Fig. 6, the magnetic induction intensity of its magnet center is stronger or equal to 3.0T. The magnetic field uniformity of its 45cm spherical imaging region after shimming is less than 10ppm, of which the magnetic field stability is less than 0.1ppm/h. Next, we will further optimize the parameters of the prototype.

![Figure 6. Test results.](image)

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