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Компенсація просторової неоднорідності розподілу магнітного поля у магніторезонансній системі

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Compensation of magnetic field spatial heterogeneity in magnetic resonance imaging system

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Пропонується методика синтезу простої шимуючої системи постійного магніту для потреб магнітно-резонансної томографії. Методика базується на нівелюванні другого порядку неоднорідності у заданій площині. Система реалізована за допомогою двох квадратних котушок. Для автоматизованого розрахунку параметрів котушок було розроблено програмний засіб. Ефективність пропонованої шимуючої системи підтверджено за допомогою комп'ютерної симуляції. Досягнуто неоднорідність коректованого магнітного поля 0,1 мТл у області розміром 20 мм, чого достатньо для створення магніторезонансної томографічної лабораторної установки.

Ключові слова: магнітно-резонансна томографія, неоднорідність, активне шимування, котушки.

The initial homogeneity of any MRI system's magnet is away from ideal specifications levels. The synthesis technique for a simple permanent magnet shimming system of magnetic resonance equipment is proposed. The previously obtained magnetic field distribution was applied to identify unwanted components in the inhomogeneous field. The technique is based on an active shimming, where currents are directed through specialized coils to improve homogeneity further. We focus on reduction of the second order magnetic field heterogeneity term in a specified plane. For each unwanted component in the uncorrected magnetic field, a carefully controlled supplemental magnetic field is generated for minimizing the number of coils. The system may be implemented with only two square coils. The author's software for automated calculation of the coils' parameters for neutralization and cancellation of the magnetic field error was developed. Computer simulations confirmed the efficiency of proposed system. The achieved inhomogeneity of corrected magnetic field is 0.1 mT within the area of $20\times10\times10$ mm^3 is enough for construction of laboratory training magnetic resonance imaging setup. Proposed technique also can be applied for reducing the higher terms of magnetic field inhomogeneity.

Keywords: magnetic resonance imaging, magnetic field, inhomogeneity, active shimming, coils.

Статтю представив д.ф.-м.н., проф. Анісімов І. О.

Introduction. Today magnetic resonance imaging (MRI) is one of the leading methods for noninvasive diagnostic of living objects. This method is based on the nuclear magnetic resonance phenomenon i.e. sampling the electromagnetic response of atomic nuclei in the superposition of oscillating and static magnetic fields. The main component of magnetic resonance (MR) scanner is the polarizing magnet that provides a highly-homogeneous static magnetic field. This magnet regardless of type (permanent, resistive, superconducting), has magnetic field inhomogeneity, which leads to a distortion of a reconstructed image pixels' values and spatial distribution. Decreasing of the field's inhomogeneity leads to decrease the effective spin-spin relaxation time that affects signal attenuation, broadening of spectral lines and deterioration of resolution in turn [1]. A spatial distortion rises from the fact that signal's frequency obtained from the certain object's regions in the inhomogeneous magnetic field does not correspond to the expected frequency of excitation radio pulse, phase and frequency encoding. To avoid such distortion the inhomogeneity of static magnetic field B_0 in the magnet's volume should be about 10^{-5} T [2].

Creation of large magnets with a specified level of inhomogeneity is a very difficult task. For correcting of the field's inhomogeneity passive and active shimming approaches are used. Passive shimming is performed by the placing of ferromagnetic plates inside the MRI system. This method has significant drawbacks: changing the magnetic properties of ferromagnetic under the influence of temperature and the impossibility of adjusting irregularities caused by the patient's body during his MR study. The idea of active shimming is in placing of coils with specific form and current inside the magnet for creation of magnetic field that compensates the inhomogeneity of B_0 field. The problem of shimming coils synthesis for known field distribution is fairly nontrivial. Several practical methods [3, 4] for synthesis of shimming coils exist. In this paper we simulated the shimming system (SS) for a permanent magnet with a high magnetic field inhomogeneity that is comparable with the magnetic field itself.

Methods. The permanent magnet (Fig. 1) has two poles with diameter and the distance between them – 7 cm. Magnetic field induction in center is 250 mT. The magnetic field distribution between the poles of the magnet is assumed to have an axial symmetry that was proved by measurements [5]. The proposed SS consists of two square coils placed inside the magnet (Fig. 1.) Square coils' form was chosen for development simplicity. According to [5] the distribution of the magnetic field is:

$$B_M = 245.703 - 0.11x - 0.23z - \\ -0.01xz - 0.04x^2 + 0.08z^2, \quad (1)$$

the field's induction is in mT, coordinates – in mm. The center of the coordinate system (CS) does not match the isocenter of the magnet. Thus displacement of the CS was applied. After that (1) was transformed to:

$$B_M = 245.634 - 0.01xz - 0.04x^2 + 0.08z^2. \quad (2)$$

The final field distribution along Z axis is:

$$B_{Mz} = 245.634 + 0.08z^2. \quad (3)$$

The inhomogeneity along Z axis is described by the second order polynomial:

$$B_{Sz} = B_S^{(0)} - 0.08z^2 \quad (4)$$

So the compensation coils should provide the corresponding special magnetic field dependence.

The value of the coefficient $B_S^{(0)}$ is not essential.

The field distribution of the single coil is the superposition of fields from four rectilinear wires with finite length. For simplicity the diameter of wires considers infinitesimal. Applying the Biot-Savart-Laplace law gives wire's spatial field distribution:

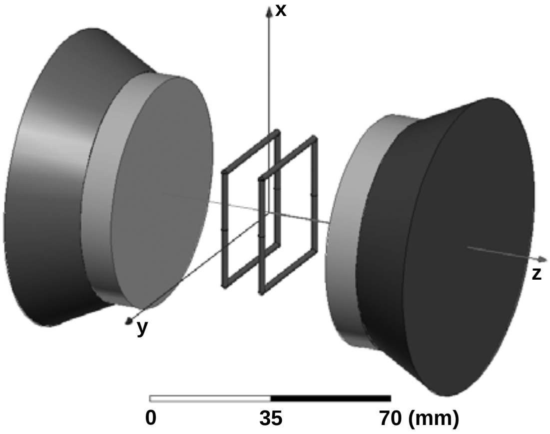

Fig. 1. Relative position of the magnet and coils

$$B_1 = I\mu_0\mu\left(\cos\varphi_1 - \cos\varphi_2\right)/4\pi r_0, \quad (5)$$

where r_0 – distance from point to wire, φ_1, φ_2 – angles between direction of current I and lines, that connect ends of the wire and spatial point. For the wire of length $2b$ and the spatial point equidistant to the wire's ends (Fig. 2) (5) can be rewritten:

$$B_2 = \frac{I\mu_0\mu b}{2\pi r_0\sqrt{b^2 + r_0^2}}. \quad (6)$$

Thus the magnetic field at the point A that is moved from center of CS at the distance s (Fig. 2) is as follows:

$$B_2 = \frac{I\mu_0\mu b}{2\pi\sqrt{s^2 + b^2}\sqrt{s^2 + 2b^2}}. \quad (7)$$

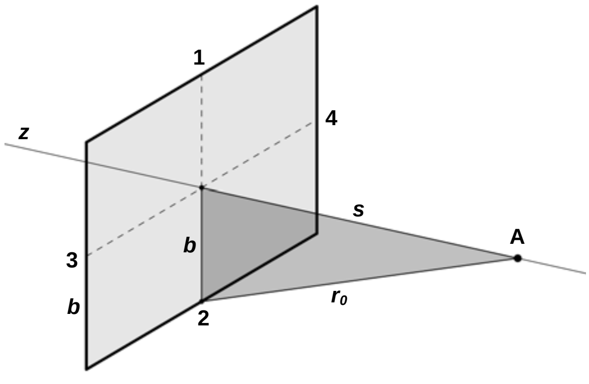

Fig. 2. Field from single wire of the coil

Considering that induction is a vector and its transversal components $\vec{B}_{\perp}$ are compensated (Fig. 3), the field from each wire is given by the equation:

$$B_i = \frac{\mu_0 \mu I b^2}{2\pi\left(s^2 + b^2\right)\sqrt{s^2 + 2b^2}}. \tag{8}$$

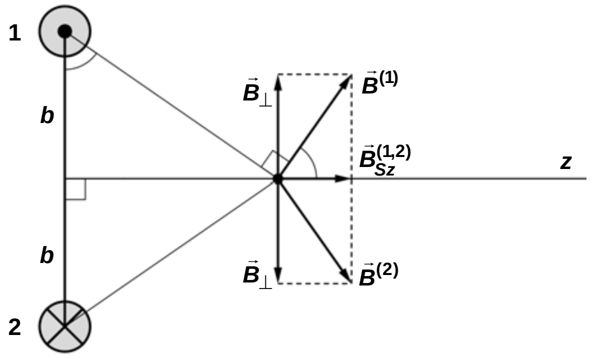

Fig. 3. Field from two wires of the coil

Field from the single coil is a superposition of the fields from all four wires:

$$B_{S1} = \frac{2I\mu_0 \mu b^2}{\pi\left(s^2 + b^2\right)\sqrt{s^2 + 2b^2}}. \tag{9}$$

Described SS has several limitations:

- currents are low for heating prevention;
- small size, that is sufficient for a placing an object 10×10×10 mm, in the region of homogeneity;
- distance from isocenter to the center of the coil is less than 35 mm for avoiding magnet poles effects.

The synthesis problem in analytic form is very complicated. We applied the much simpler "brute force" approach for coils parameters determination. Such parameters are: *b*, *s*, *I*.

Computing automation. Taking into account the large number of parameters' variations and the needs for approximation it was decided to create the software for automated calculation of SS parameters. The software was developed using Visual Studio 2010, programming language is C#. Software has user-friendly Graphical User Interface that allows interactive monitoring of the calculations' progress.

The algorithm has the following steps:

1. Shimming field distributions along Z-axis is calculated in 40 points located from -35 to 35 mm.
2. Data is approximated by 4÷8 degree polynomial using the ordinary least squares method.
3. Quadratic term of this polynomial is compared to the inhomogeneity term (3). If they match within tolerance, calculated parameters are added into the result area.
4. Parameters are increased by the step value. Calculation continues from the step 1 until the parameters reach their final values.

Results. For preliminary evaluation of the SS the parameters synthesis was performed in the wide range and with large step. The obtained parameters distribution is described on Fig. 4. Balls on the graph correspond to parameters that meet (4). Also this graph shows the needs increasing the current while the coil is enlarged.

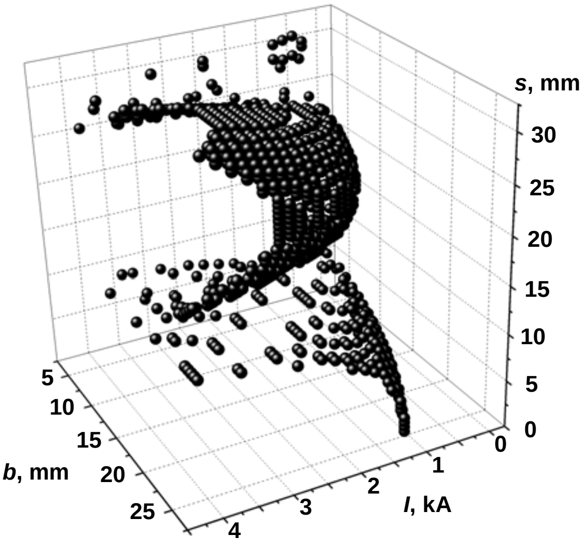

Fig. 4. Rough estimate of the parameters boundaries

The optimal SS parameters that correspond to smallest current are as follows: $I = 1076$ Ampere-turns, $b = 19.3$ mm, $s = 7.94$ mm. Polynomial that describes the SS magnetic field is as follows:

$$\begin{aligned} B_{Sz} = {} & 52.3 + 1{,}1\cdot 10^{-16} z - 0{,}08 z^2 - \\ & -9{,}4\cdot 10^{-19} z^3 + 5.5\cdot 10^{-5} z^4 + \\ & +9{,}4\cdot 10^{-22} z^5 - 1.4\cdot 10^{-8} z^6. \end{aligned} \tag{10}$$

Magnetic field along Z-axis after shimming is described in Fig. 5, line 2.

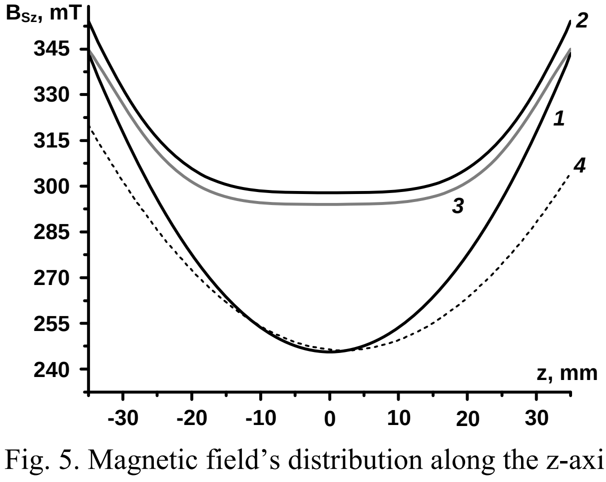

Fig. 5. Magnetic field's distribution along the z-axis

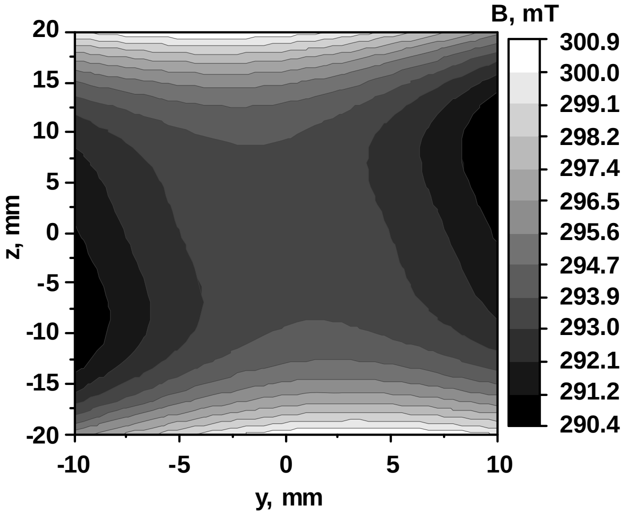

Fig. 6. Results comparison in plane yOz

Filed inhomogeneity obtained in present work (line 2) outperforms the previously obtained inhomogeneity for the same magnet (line 4) [6]. Thus inhomogeneity along Z-axis was decreased 45 times to $\Delta B \approx 0.1$ mT in area 20 mm, compared to magnet without SS (line 1).

The simulation in ANSYS Maxwell 3D 16.0 was performed to verify the obtained SS characteristics. Simulated magnetic field distribution proves field inhomogeneity (Fig. 5, line 3 and Fig. 6). Magnetic field distribution after compensation with the proposed SS was calculated and described on Fig. 6. Field distribution is rotated around the x-axes because polynomial (2) has term $-0.01xz$. Incompatibility between line 2 and line 3 (Fig. 5) is explained by the limitations of the SS.

Conclusion. Proposed simple active shimming system compensates the quadratic term inhomogeneity of permanent magnet's field. The achieved relative inhomogeneity is 10^{-4} that is enough for magnetic resonance imaging. Designed software can serve as a tool for design, calculation and optimization of shimming, gradient and other coils of MRI scanners. Described method can be used in X and Y-directions. The practical implementation of the coils should provide the possibility to move the coils along all axes in the range of ±5 mm and the rotation around each axes in the range of ±15°. The main shortcoming of this system is relatively large currents in the coils. Future work may be related to design the shimming system that compensates the higher order terms in magnetic field spatial dependence.

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