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A study on the optimized design of low-order shimming coils for high-temperature superconducting magnets

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Abstract

In this paper we present design and optimization of shimming coils to correct low-order field gradient components deteriorated by screening currents in high-temperature superconducting (HTS) NMR magnets. The unique geometry of HTS wires induces screening currents, which generate low-order field gradients that degrade the magnetic field quality. To compensate the low-order field gradients, high-strength low-order shimming coils were designed. At first, the target field method was employed to derive the initial shapes of the shimming coils. Subsequently, a genetic algorithm (GA) was utilized to optimize the coil geometries, ensuring ease of fabrication while maintaining high performance. The performance of the optimized coils was validated through virtual field mapping and COMSOL simulations, demonstrating their effectiveness in compensating for targeted gradients with correction efficiencies exceeding 99%. The experimental evaluation will be carried out following the fabrication of the shimming coil in accordance with the proposed design.

Keywords: field gradient, HTS NMR, screening current, target field method

1. INTRODUCTION

The performance of nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) systems strongly depends on the strength and spatial homogeneity of the magnetic field. Due to the critical field limitations of low-temperature superconductors (LTS), which are typically below 23.5 T, high-temperature superconductors (HTS) are required to generate high-field magnets. However, the unique shape of the HTS wires generates screening currents, which significantly degrade the temporal stability and further degrade the spatial homogeneity [1-3].

To mitigate the issue of field quality caused by screening currents, shim devices are utilized, with room-temperature shimming (RT-shim) serving as a form of active shimming capable of compensating for the harmonic components of the magnetic field in real time [4, 5]. Conventional shimming coil sets are designed to operate in LTS magnets, where the effects of screening currents are nearly negligible. As a result, the shimming strength for low-order gradient components, which are highly sensitive to screening current effects, is relatively low. To enhance the field quality of HTS NMR and MRI systems, which are significantly affected by screening current effects, a shimming coil design with relatively stronger low-order gradient shimming components is required [1-3].

The target field method and optimization algorithm were employed to design shimming coils suitable for HTS magnets [6, 7]. Firstly, the target field method was adopted to derive the initial shapes of each shimming coil. Subsequently, Genetic algorithm (GA), which is one of the optimization methods, was employed to determine the detailed specifications and winding patterns of the shimming coils [8].

Using the proposed method, a low-order shimming coil set was designed to meet the specifications of Korea Basic Science Institute (KBSI) 400 MHz all-HTS NMR magnet. Numerical analysis techniques were employed to verify the magnetic field gradient distribution generated by each shim coil. Furthermore, the magnetic field distribution was cross-validated using COMSOL simulations. The optimized shimming coil design achieves correction efficiencies exceeding 99% for all major gradient components. Furthermore, the proposed coil designs are planned for future fabrication and subsequent integration into the 400 MHz HTS NMR magnet at KBSI, aiming to improve magnetic field stability and homogeneity to fulfill the demands of high-precision applications.

2. OPTIMIZED DESIGN OF THE LOW ORDER SHIMMING COILS

2.1. Design method

To actively improve degraded spatial homogeneity, the RT-shim technology is adopted to compensate for each harmonic component that affects magnetic field quality. The target field method, which is a technique determine the path of current flow along the shimming coil area to achieve the desired magnetic field distribution within the target region, was employed to design the RT-shimming coil that meets these requirements [6, 7]. The shimming coil area and the target region are represented in Fig. 1. The

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governing equation of the method is shown in Equation (1), where B_Z ($\boldsymbol{c}$; $\boldsymbol{\theta}$,$\boldsymbol{z}$) is the target field density, and $j_\theta(\theta', z')$ is the current density at the shimming coil area, which is the goal of the calculation. The additional parameters a, c, L and qL are represented in the Fig. 1.

$$B_z(c,\theta,z) = -\frac{\mu_0 a}{2\pi}\int_0^{2\pi}\int_{-L}^{L}[c\,cos(\theta-\theta') - a]\; j_\theta(\theta',z') \times [c^2 + a^2 - 2accos(\theta-\theta') + (z-z')^2]^{\frac{-3}{2}}\, dz'd\theta' \quad (1)$$

$$,pL < z < qL$$

The derived current density $j_\theta(\theta', z')$ is converted into the stream function $\psi(\theta', z')$, which represents winding pattern of the shimming coils. The relation between the two parameters are as follows [6, 7].

$$j_\theta = \frac{\partial\psi}{\partial z} \quad \text{and} \quad j_z = -\frac{1}{a}\frac{\partial\psi}{\partial\theta} \qquad (2)$$

After the initial shapes of the shimming coils are determined using the target field method, the detailed specifications of each coil are subsequently optimized through a GA-based approach. In the optimization design of the shimming coils, the number of turns and dimensions of the coils are defined as design variables. The objective function is formulated to maximize the desired gradient component by setting the ratio of the target gradient component to the sum of all gradient components. The detailed optimal design method is as follows. Based on the principles of GA, a solution set composed of coil design parameters is generated for the population size, and the objective function for each set is evaluated. A few high-ranker sets are selected, and through crossover and mutation, new sets are created. This process is repeated over multiple generations, ultimately leading to the optimal design of the shimming coil [8]. The Fig. 2 represents the flow-chart of the optimized design process.

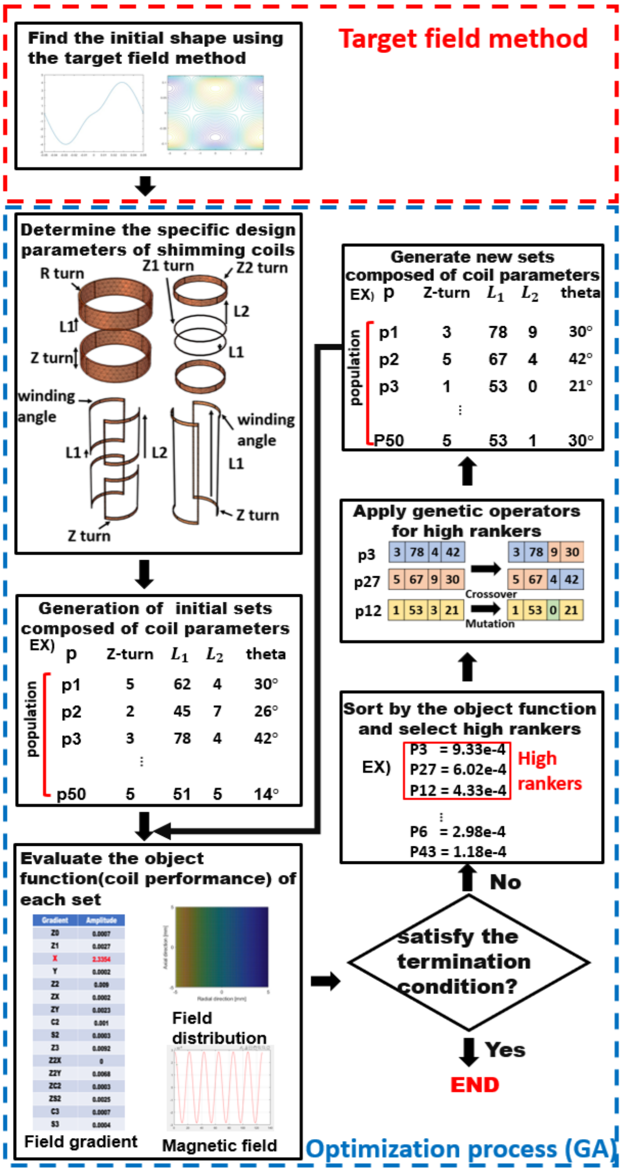


Fig. 2. Flow chart of the optimized design method.

2.2 Design results

Based on the aforementioned shimming coil optimization technique, a low-order shimming coil (Z1, Z2, X, Y, ZX, ZY) design suitable for KBSI all-HTS NMR magnet was developed. Considering the room-temperature bore size and dimensions of the NMR measurement probe, design constraints were applied to ensure that the winding diameters of the shimming coils range between 40 mm and 66 mm. In addition, copper wires with a diameter of 0.6 mm were used to enhance the strength of the shimming coil.

The calculated current density of zonal shimming coils (Z1, Z2) and the stream functions of tesseral shimming coils (X, ZX) by using the target field method are represented in Fig. 3 and Fig. 4, respectively. The geometries of the Y and ZY components are identical to those of the X and ZX component coils, respectively. Using the calculated current density and stream function, the initial shapes of each shimming coil were derived. Subsequently, the specific number of turns and detailed specifications were determined through an optimization process, as illustrated in Fig. 5.

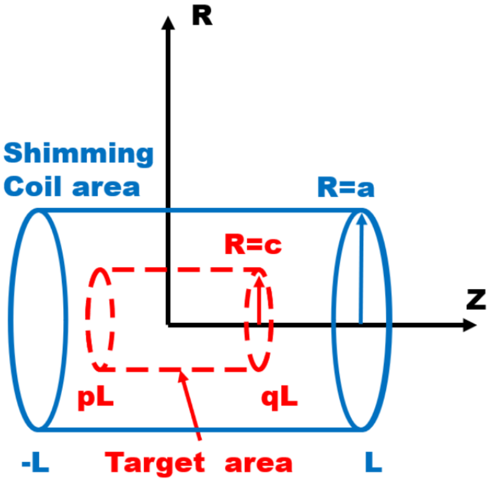
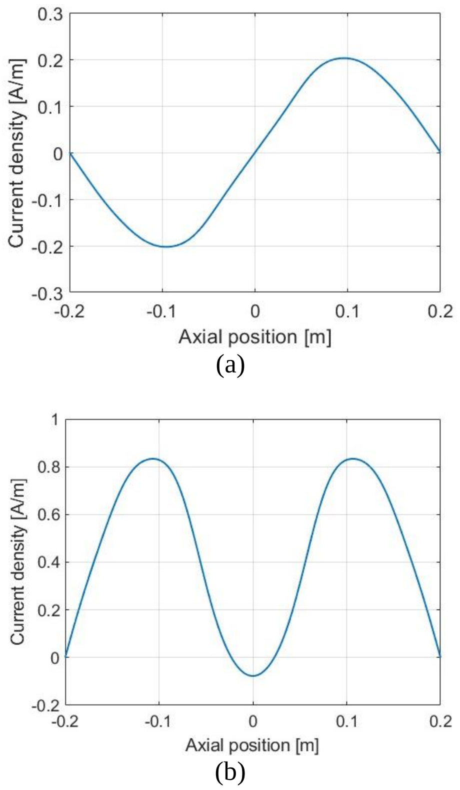


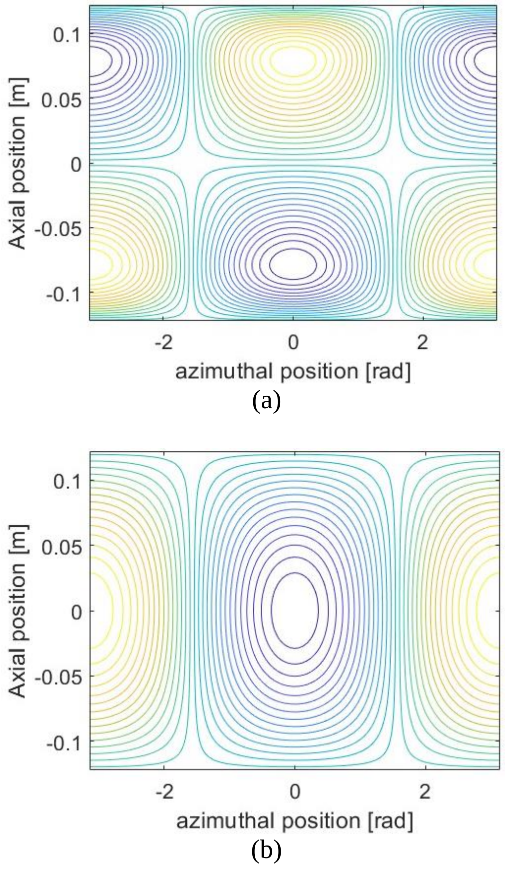
Fig. 1. Configuration of the shimming coil area and the target area for target field method.



(a)

(b)

Fig. 3. Current density with respect to the axial position derived through target field method: (a) Z1 coil (b) Z2 coil.



(a)

(b)

Fig. 4. Stream function, which represents winding pattern of the coils, with respect to the positions derived through target field method: (a) X coil (b) ZX coil.

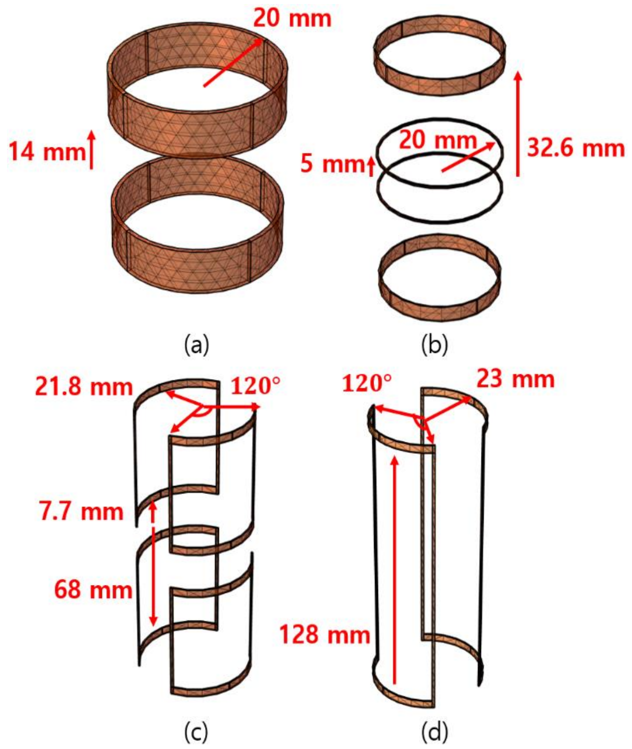


Fig. 5. Configuration of the shimming coil derived through optimal design: (a) Z1 coil (b) Z2 coil (a) X coil and (d) ZX coil.

3. VALIDATION OF THE SHIMMING COIL DESIGN

3.1. Verification of field gradient components Using Numerical Analysis

The field gradient was analyzed using virtual field mapping to validate the performance of the shimming coil derived from the optimal design. In the virtual field mapping, the z-direction magnetic field (B_Z) was calculated at a total of 128 points along the outer surface of a cylinder with a radius of 5 mm and a height of 10 mm, rotating helically at intervals of 16.9203° for a total of six revolutions. Using the 128 magnetic field values obtained in this manner, the magnetic field gradient components, including terms up to the third order, can be derived [9]. The Table I represents the calculated field gradients for the shimming coils. The ratio of the target component generated by each shimming coil to the sum of all components is 99.9% for the Z1 coil, 99.5% for the Z2 coil, 99.3% for the X coil and 99.9% for the ZX coil, respectively. This demonstrates that the efficiency of the designed shim coils is remarkably high.

To visually evaluate the magnetic field gradients generated by each shim coil, the magnetic field distribution near the center was calculated for each coil when shimming coil current was applied, as shown in Fig. 6. The magnetic field strength is observed to vary in accordance with the colors depicted in the Fig. 6. In Fig. 6(a) and (b), the magnetic field exhibits linear and quadratic variations, respectively, along the axial direction (z-direction). Furthermore, in Fig. 6(c), it varies linearly along the radial direction (x-direction), whereas in Fig. 6(d), it is observed to vary depending on both the axial and radial directions.

Fig. 6 demonstrates that each shim coil effectively generates the corresponding field gradient components.

3.2. Verification of magnetic field distribution Using Finite Element Method (COMSOL)

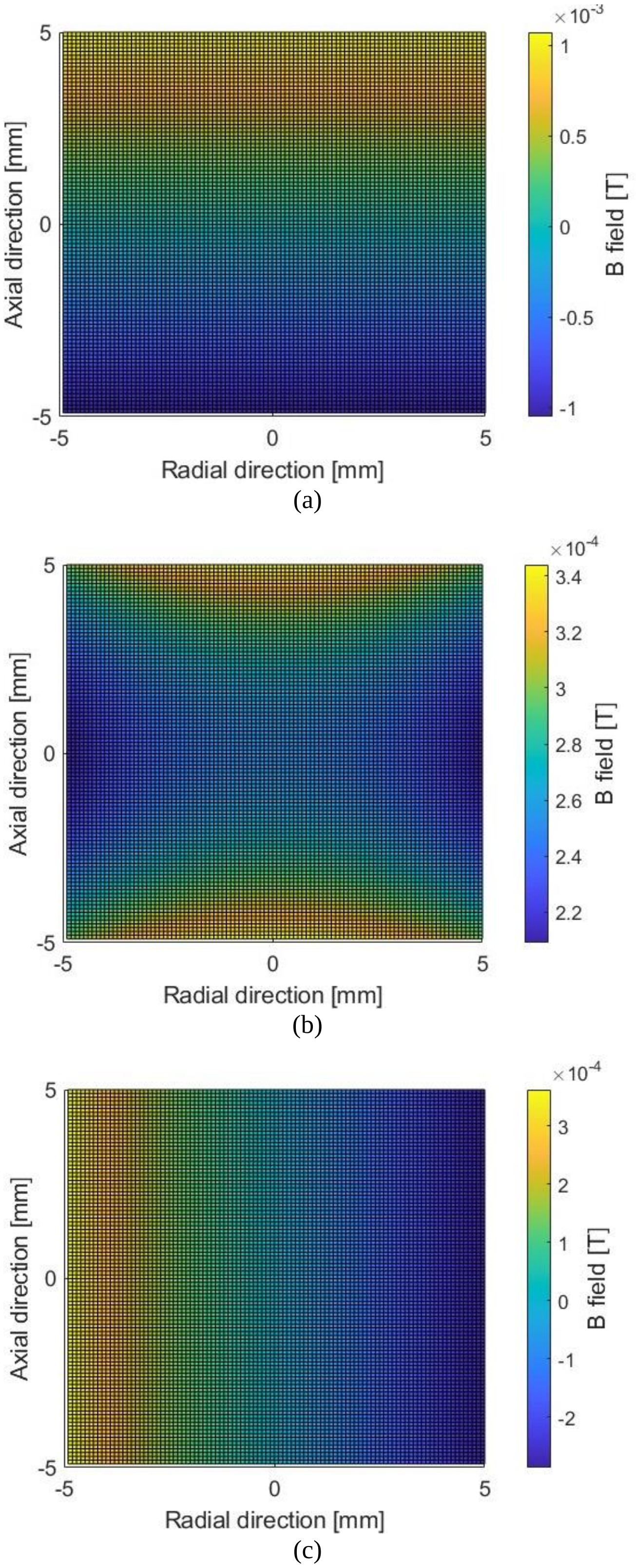
Using COMSOL, the optimally designed geometry was modeled, and the field gradient distribution was evaluated. The magnetic field values at the coordinates along the virtual mapping path introduced in Section 3.1 were calculated using COMSOL and compared with the numerically computed values obtained from MATLAB calculations. Fig. 7 shows comparison graphs of the magnetic field distributions calculated using COMSOL and MATLAB along the mapping path. The commercial finite element analysis software COMSOL produced results identical to the magnetic field distributions of the shimming coils designed using MATLAB, confirming the effectiveness of the proposed design method. Therefore, the field gradients calculated using COMSOL are almost identical to those in Table I.

4. CONCLUSION

This study presents optimized design of the low-order RT shimming coils for 400 MHz all-HTS NMR magnet. The initial shapes of each shim coil were determined using the target field method, and the detailed specifications and number of turns for the shimming coils were optimized using GA. The method enabled the efficient design of shimming coils capable of generating specific components exclusively. That is, the gradient components generated by the shimming coils designed using this approach account for over 99% of the total gradient components. Their performance was cross-validated using numerical analysis techniques and COMSOL. In the future, shimming coils for the 400 MHz all-HTS NMR magnets will be fabricated based on the designs developed in this study. After installation, operating tests will be implemented to evaluate the performance of the shimming coils.

TABLE I
Field Gradients of the derived shimming Coils.

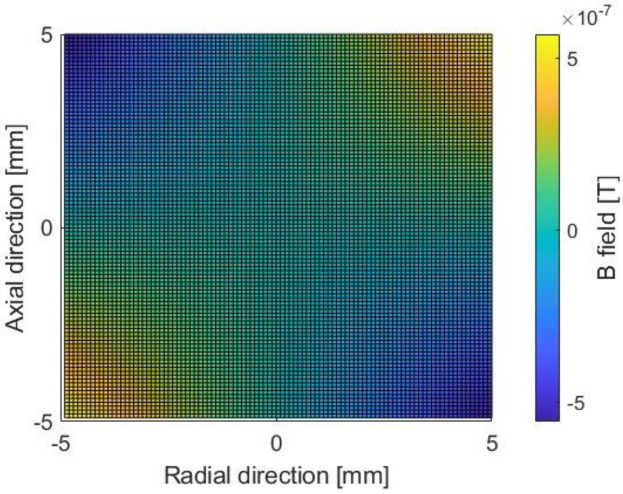
	Z1 coil	Z2 coil	X coil	ZX coil
Z0 [kHz]	0.0000	0.0030	0.000	0.000
Z1 [kHz/cm]	27.3656	0.0001	0.000	0.000
X [kHz/cm]	0.0000	0.0000	2.444	0.000
Y [kHz/cm]	0.0004	0.0000	0.000	0.000
Z2 [kHz/cm^2]	0.0005	1.1623	0.002	0.000
ZX [kHz/cm^2]	0.0030	0.0005	0.000	0.009
ZY [kHz/cm^2]	0.0002	0.0000	0.000	0.000
C2 [kHz/cm^2]	0.0001	0.0000	0.000	0.000
S2 [kHz/cm^2]	0.0006	0.0000	0.000	0.000
Z3 [kHz/cm^3]	0.0002	0.0003	0.003	0.000
Z2X [kHz/cm^3]	0.0021	0.0001	0.000	0.000
Z2Y [kHz/cm^3]	0.0162	0.0012	0.001	0.000
ZC2 [kHz/cm^3]	0.0034	0.0001	0.000	0.000
ZS2 [kHz/cm^3]	0.0005	0.0003	0.004	0.000
C3 [kHz/cm^3]	0.0002	0.0000	0.000	0.000
S3 [kHz/cm^3]	0.0007	0.0001	0.000	0.000



(a)

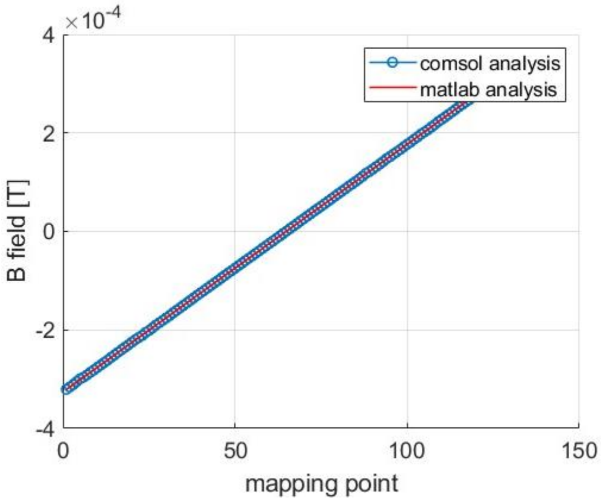
(b)

(c)

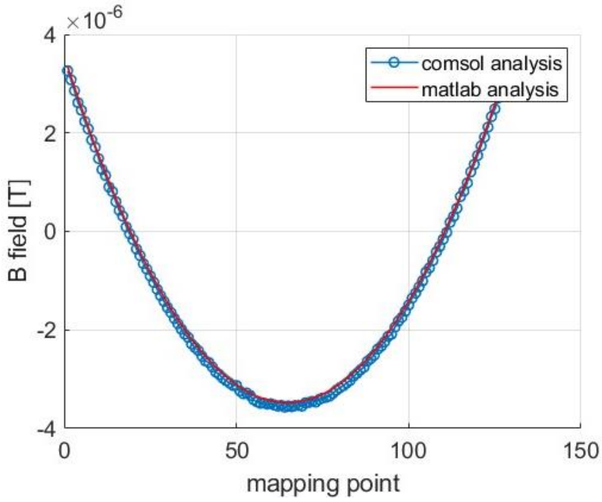


(d)

Fig. 6. Field distribution near the magnet center when the shimming coils were applied: (a) Z1 coil (b) Z2 coil (c) X coil and (d) ZX coil.



(a)



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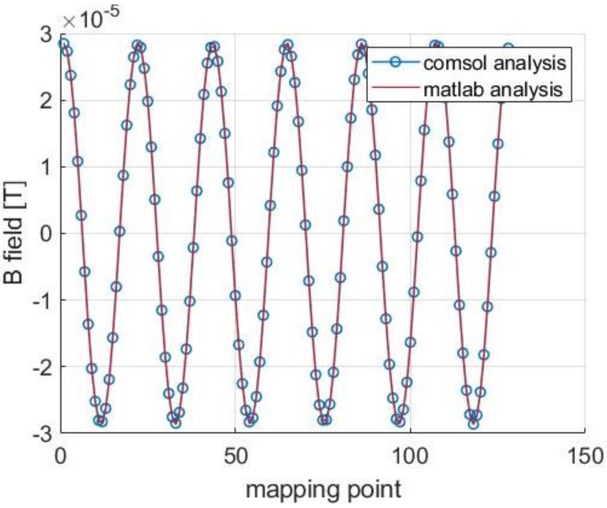
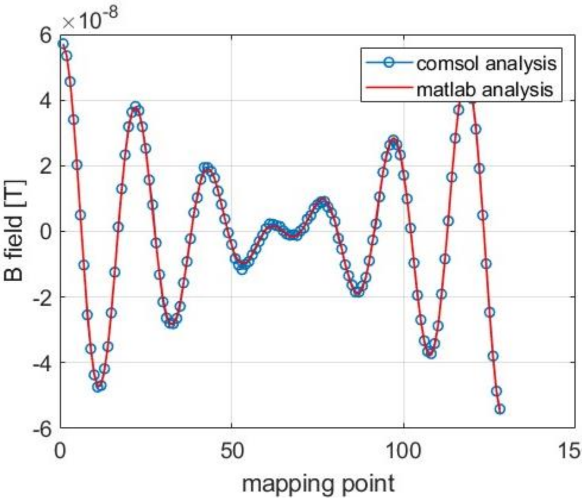


(c)



(d)

Fig. 7. Comparison of field mapping results between MATLAB and COMSOL: (a) Z1 coil (b) Z2 coil (c) X coil and (d) ZX shim coil.

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