Magnetically Shielded Highly Homogeneous Systems Development Using Comsol Multiphysics

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Abstract. The article discusses the effect of cylindrical shielding shells on the uniformity of the magnetic field created by coil sources used in measures of low-field induction. Calculations were carried out to adjust the parameters of such sources in order to increase the homogeneity of the magnetically shielded system field.

INTRODUCTION

Homogeneous magnetic field is a useful tool for the implementation of various tasks in science and technology. There are many approaches to solving the problem of creating a uniform field in the laboratory. The concepts underlying these solutions largely depend on the specifics of the task: from the required uniformity, geometric shapes and sizes of the workspace, maximum magnetic field gradients arising in the workspace, the range of required magnetic inductions. Creating a measure of the magnetic induction of weak fields requires the simultaneous solution of two problems: the screening of an external magnetic field and the creation of a uniform field in the workspace. There are many papers in which these problems are discussed separately. For example, the authors of [1–3] give both analytical expressions for calculating the shielding of cylindrical shells, and calculated multi-layered screen designs. Regarding the sources of homogeneous fields, there are many works analyzing the homogeneity of coil systems [4–6], the authors of [7] give an extensive list of measures of magnetic induction, with mathematical calculations in relation to their homogeneity. Undoubtedly, shielding shells are useful in such devices, since they allow work to be conducted in a conventional laboratory. However, as will be shown below, when the optimized source of a uniform field is located in the shielding envelope, additional magnetic anomalies arise in the system due to the presence of current sources near the magnetic substance. Such fictitious field sources change (worsen) uniformity in the workspace.

The materials of this article are mostly of an applied nature and are aimed at creating a constant-field measure, which by its characteristics will allow working with POS magnetometers, including vector POS-4, on the basis of a scalar one [8]. A system of cylindrical shape (with open ends) will be considered, since such a shape is most convenient for devices to access the workspace.

Special attention will be paid to the influence of the shell on the magnetic field created. The question of the effective shielding of an external magnetic field seems to be simpler. Based on the expressions given in [1,2], it can be concluded that the best positioning of the screen relative to the external field (namely, setting the screen axis perpendicular to the horizontal component of the external magnetic field) minimizes the non-uniformity in the center. With this arrangement, the magnetic field penetrating into the workspace is minimal. Of course, the system for creating a uniform field in the laboratory must undergo a primary setting, since it is impossible to completely avoid the influence of an external field. In our case, to ensure better uniformity, adjustment of the shunt resistance is provided, which controls the ratio of currents in the composite solenoid. The smooth adjustment of this resistance will to some extent compensate for the heterogeneity that has arisen due to the effect of an external field.

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DEVICE STRUCTURE

The developed measure of magnetic induction constructively consists of a solenoid placed in a multilayer cylindrical shell with open ends. Shell material – permalloy ($\mu \sim 10^4$), steel. In the center of the solenoid there is a section in which the current differs in value from the current in the rest of the coil. The current in the solenoid is set using a stable, high-precision source. The appearance of the system design is shown in Fig. 1.

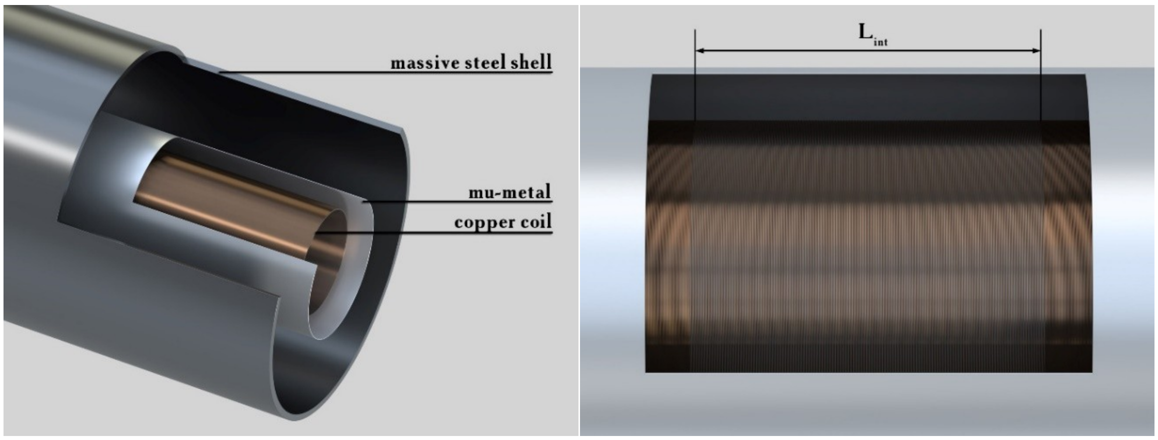

FIGURE 1. System construct. In the center of the solenoid there is a section of the length L_{int} of the same diameter in which the winding pitch is increased (the current density is reduced)

The task of the outer layer (several layers) is to screen the main external field. The role of the outer layer can perform several thin layers of metal with high magnetic permeability. A constant magnetic field penetrating into the screen, as well as its heterogeneity, is attenuated by 3-4 orders of magnitude [3, 9], which is confirmed by numerical calculations. The parameters of the section with a modified winding step (modified current density) of the solenoid will be set during the calculation.

The Influence of the Magnetic Screen on the Solenoid Field

It is known that a finite-sized solenoid creates a non-uniform magnetic field at the geometric center. Before introducing a corrective section into a solenoid (like on Garrett solenoid), we examine how the shell affects the uniformity of the field it creates.

Magnetic Field Uniformity Criterion

There are many ways to find out how uniformly the magnetic field. The uniformity criterion in the workspace can be the RMS of the magnetic field modulus, the maximum values of the gradient, the equality to zero of coefficients of the n^{th} order in the field decomposition [7]. Since it is assumed that the calculations of the system will be performed numerically, we will abandon the zeroing of the coefficients of the derivatives in the decomposition. It is also known that the magnetic field will be created by two coaxial solenoids, which means that there will not be high field gradients in the workspace. As a criterion of homogeneity, let us dwell on the difference between the maximum and minimum values of the modulus of the magnetic field ΔB within the central sphere with a radius of 50 mm in the range of magnetic inductions 20–100 μT. This criterion makes it possible to indirectly estimate the magnitudes of the gradient in the workspace, since the shapes of streamlines of the modulus of the magnetic field in the central region are known.

Calculation of the Solenoid-Shell System

Consider the solenoid-shell system, in order to establish the effect of the shell on the uniformity of the magnetic field. Let us set the linear dimensions of the system, satisfying the conditions of work with the equipment POS-4.

The length of the solenoid - 2 m, diameter - 500 mm. We plot the magnetic field for a solenoid with and without a shell (Fig. 2).

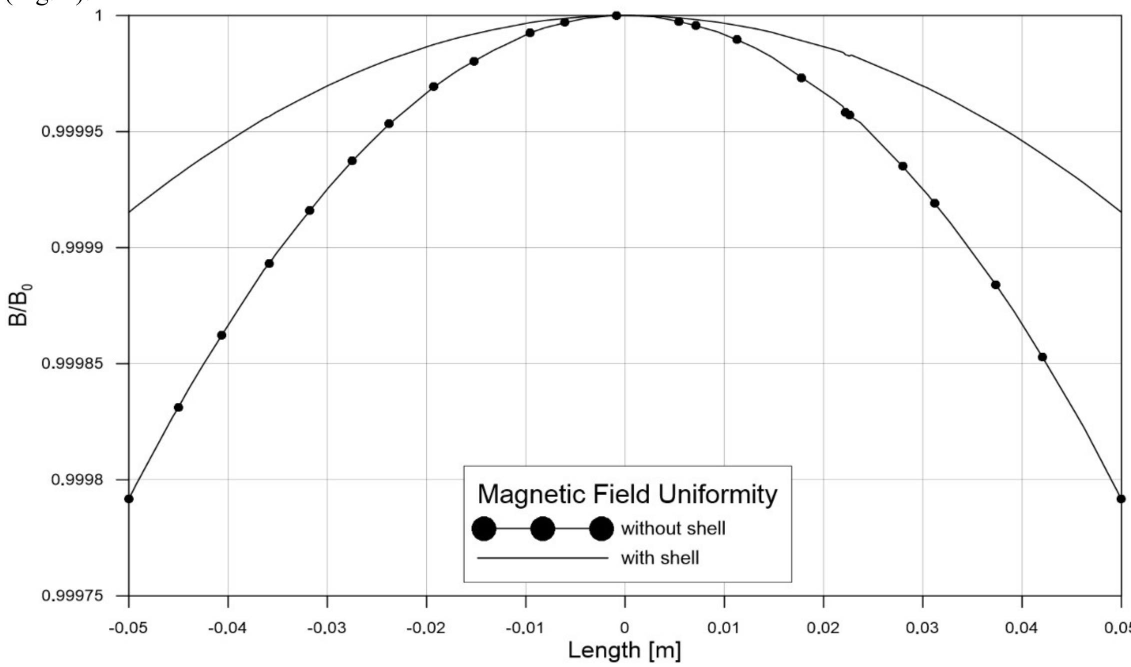

FIGURE 2. Magnetic field modulus along the axis of the solenoid normalized to the central field (shell parameters: length 2 m, diameter 0.7 m, thickness 2 mm, $\mu = 10^4$)

As can be seen from the figure, the uniformity in the workspace has increased, but the influence of the shell, depending on its parameters, is still unknown. We will carry out a parametric analysis (of the length and diameter of the shielding shell), which will allow us to find out how these parameters affect the field created and its homogeneity. By calculating such dependencies, you can easily pick up the shell for a pair of solenoids placed inside. The results of the analysis are presented in Fig. 3.

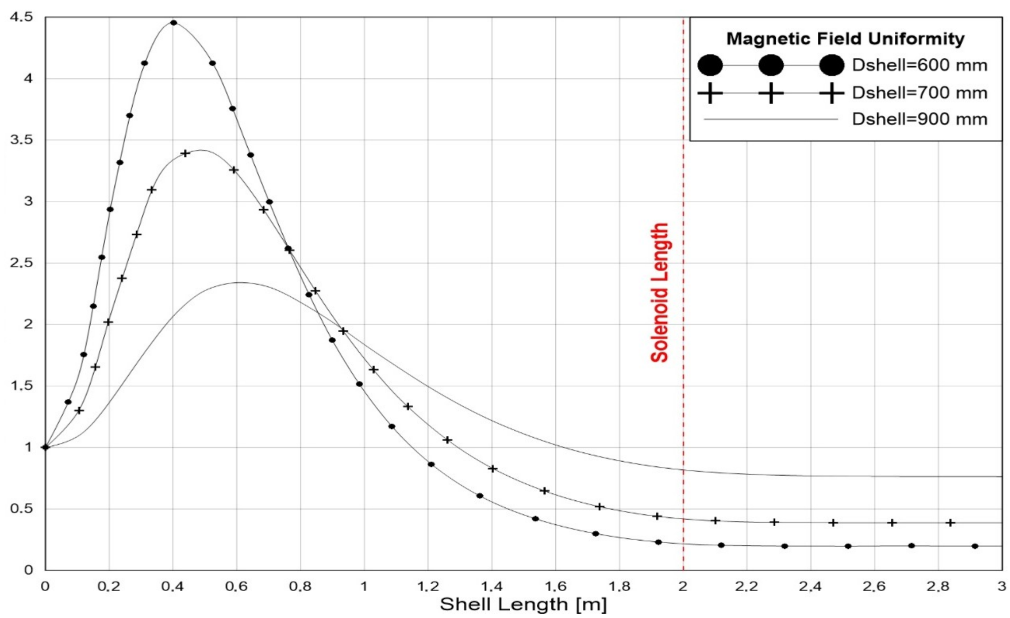

FIGURE 3. Relative (reduced to inhomogeneity of a simple solenoid) inhomogeneity of the magnetic field in the workspace, depending on the length and diameter of the near shielding shell

As can be seen from the figure, with the proximity of the shielding shell to the solenoid, its influence on the created field and uniformity in the workspace increases. It should be noted that the obtained curves are calculated for a solenoid with a certain ratio of length and diameter, for other solenoids they will always have such a shape, but will differ in amplitude. Moving along the selected curve, it is possible to achieve the state that the shell does not affect (according to the chosen criterion) the uniformity of the solenoid field in the workspace. We take advantage of this fact when selecting the length of the shell; we will choose its diameter equal to 600 mm, based on economic reasons.

Calculation of the Correction Coil Parameters

As the initial solution of the problem, we use the solution obtained during the calculation of the Garrett solenoid. For a coil with a length of 2 m and a diameter of 500 mm, the length of the inner section of the same diameter will be 488 mm, and the ratio of the currents of the main and central coils will be 1.019. Such a composite coil, due to analytically optimized parameters, creates a highly uniform field in the workspace. Achieve high uniformity should be due by the selection of screen parameters, without changing the parameters obtained in the course of solving the problem of the Garrett solenoid.

The central part of the solenoid with a reduced current density can be represented as a counter-activated solenoid with a current $J_{int}^{*}=J_{ext}-J_{ext}/1.019$, where J_{ext} – current in the main coil. After analyzing the effect of the shell parameters on both solenoids, it is possible to choose the shell length at which the field inhomogeneity will be equal for both coils. The result of the analysis is shown in Fig. 4. In this case, we present the difference between the emerging fields in the workspace (at a current of J_{ext}=50 mA; D_{shell}=600 mm).

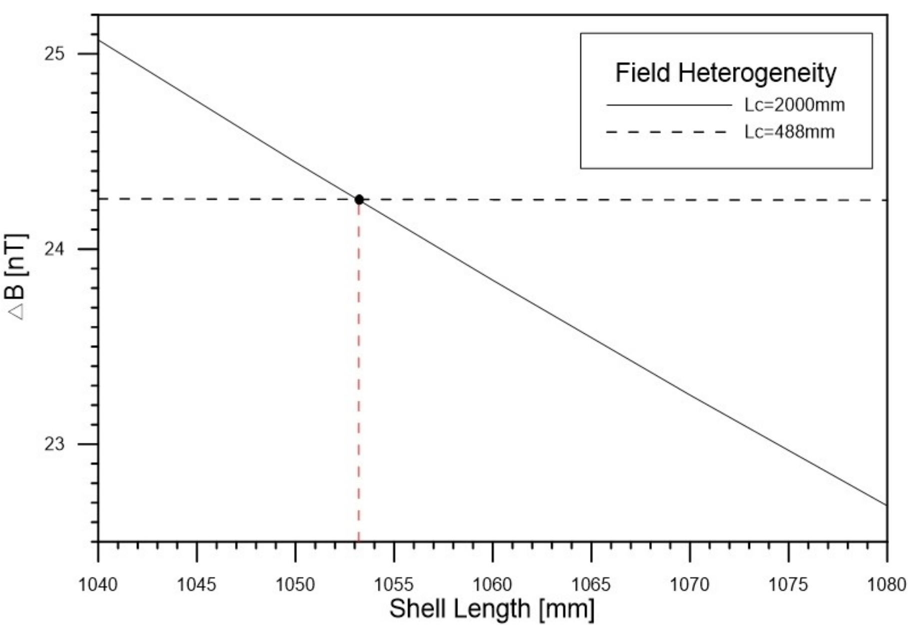

FIGURE 4. The difference between the maximum and minimum values of the magnetic field within the workspace, for two coils (488 mm – int. coil, 2000 mm – ext. coil), depending on the length of the shell

Using Fig. 4, we find the optimal length of the shell L_{shell}=1053.14 mm, at which the total inhomogeneity of the composite solenoid will be minimal. In fact, the difference between the values of ΔB for each of the coils will be equal to the total inhomogeneity, and at the intersection points of the graphs it is closest to zero (not equal zero, due to the differences in the shapes of the equi-surface of magnetic field for two coils).

We now construct a graph of the magnetic field, within the workspace, along all three axes, using all the parameters found for the coils and the shell (Fig. 5). It should be mentioned that the heterogeneity values shown in the figure may be even smaller, but at the initial decision stage, the length of the inner section was rounded to integer values, assuming that the coil is wound with a wire of 1 mm diameter.

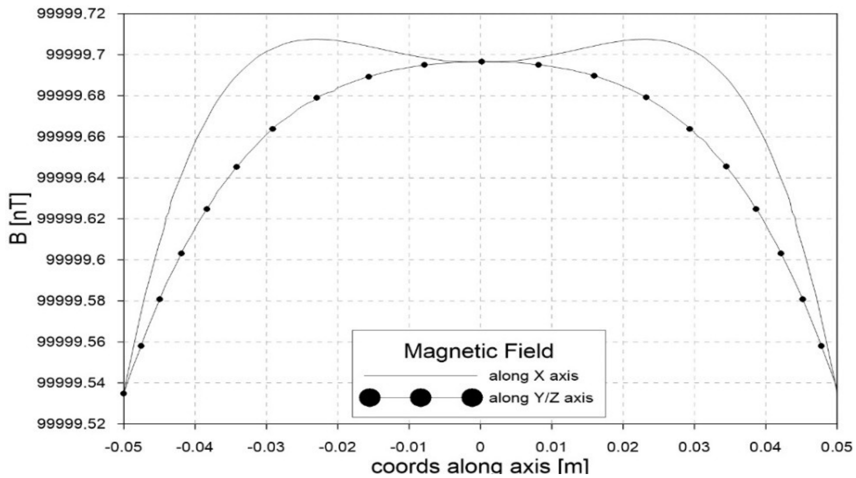

FIGURE 5. Magnetic field in the workspace created by a system from a Garrett solenoid and a specially designed shell (X axis – solenoid axis, Y/Z axis – transverse axis)

As can be seen from the figure, the calculated structure has an inhomogeneity in the working area of ~ 0.2 nT, in the upper part of the range of required inductions. The applied approach, which considers the influence of the shell on the field of each of the coils, can be used for a multilayer screen, also achieving a zero difference between the heterogeneities of each of the coils.

CONCLUSIONS

Numerical calculation makes it possible to solve magnetostatic problems containing a multitude of objects of complex shape (include hollow cylinders with finite size). Using jointly analytical calculations and carrying out numerical experiments, it was possible to create a model of a measure of magnetic induction of a weak field with a high degree of field homogeneity in the workspace. An algorithm for optimizing the parameters of shielding shells has been developed and applied. The effect of shielding shells on the magnetic field created by coil sources is investigated. Under ideal conditions, the homogeneity of the calculated system is 100 times better than the uniformity of the solenoid in the same shell (~0.2 nT vs ~20 nT).

To correct the calculated parameters, it is planned to introduce into the model hysteresis loops of real materials, for example, permalloy (79% Ni, 16% Fe, 4% Mo). In order to create a prototype, it is planned to add several outer layers of the shielding shell to the model. In addition, the calculation of dynamic effects occurring in the near shell (induction of Foucault currents) in the process of measuring the magnetic field with POS sensors is planned, which may affect the choice of screen parameters, in particular, the diameter.

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