

Design Optimization of Interference Suppression Cores for Magnetic Field Measurement Systems Using Sensitivity Analysis

Kyungsik Seo, Eunghae Jung, and Il Han Park

Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, 16419 Korea, kseo@skku.edu

Magnetometers mounted on large magnetic carriers to monitor the target external magnetic field are affected by interfering magnetic fields generated by the carrier body, resulting in deviations from the true target value. To address this, a compensation process based on the pre-assessment of interfering fields is typically required to achieve accurate target-field estimation. However, inaccuracies in the evaluation of interference fields or operational changes in the carrier's geometry and magnetic properties can lead to residual errors that existing compensation methods cannot effectively mitigate. This paper proposes an optimal design method for an interference suppression core (ISC) to overcome such challenges. The ISC is optimized to produce an induced magnetic field that passively suppresses the interference field from the carrier body while maintaining the integrity of the target external field. The optimization method employs continuum sensitivity analysis to derive the design velocity of the ISC, ensuring compliance with the multiple design objectives. A design example validates the effectiveness of the proposed method, demonstrating the ISC's potential to reduce errors in magnetic field measurement systems.

Index Terms—Error compensation, interference suppression, magnetic field measurement, sensitivity analysis.

I. INTRODUCTION

HIGH-PRECISION magnetic field measurement plays a critical role in a wide range of applications, including resource exploration, ordnance detection, and geomagnetic navigation. However, the accuracy of these measurements is often complicated by interference fields generated by the large carriers of the magnetic sensor, which typically include ferromagnetic materials and electrical devices. These interference fields lead to deviations from the intended target field. This challenge may be mitigated by pre-assessing the interfering fields through simulation and experimentation, followed by compensating for their effects on the measured data [1], [2]. A notable feature of these error calibration methods is that they rely on error compensation models developed under stationary conditions prior to practical deployment. Consequently, unexpected deviations in the interfering fields during system operation, arising from inaccuracies in pre-assessment, or changes in system geometry, material properties, or operating currents, are directly incorporated into the measurements. These errors cannot be effectively mitigated by existing compensation methods. To improve reliability in high-precision measurement, it is crucial to minimize these distortion errors, even in the presence of unforeseen variations in interfering fields.

This paper proposes an optimization method for interference suppression through the optimal design of a ferromagnetic material positioned near the magnetic field sensing area, with the goal of enhancing the estimation accuracy. The interference suppression core (ISC) generates a magnetic field due to its magnetization, which is induced by surrounding magnetic fields. The ISC is designed to passively suppress interfering fields within the sensing area, while preserving the integrity of the target field intended for estimation. Consequently, this approach reduces estimation errors arising from unexpected deviations in interference field sources, which is critical for ensuring accuracy in high-precision measurement processes.

The design of the ISC is a multi-objective optimization problem aimed at minimizing interfering magnetic fields while preserving target measurement fields. This paper presents a multi-objective optimization method that employs design sensitivity analysis. In this optimization process, the design velocity for evolving the ISC geometry is derived through numerical analysis of the continuum sensitivities related to each objective.

II. CONCEPT OF THE INTERFERENCE SUPPRESSION CORE

The magnetic field $\mathbf{B}_m$ measured by a magnetometer can be expressed as the superposition of the target external field $\mathbf{B}_e$ and interfering magnetic field $\mathbf{B}_i$ generated by surrounding magnetic systems as follows:

$$\mathbf{B}_m = \mathbf{B}_e + \mathbf{B}_i. \quad (1)$$

The interfering fields include the induced magnetic field and permanent magnetic field from ferromagnetic materials, as well as the current-induced magnetic field produced by operating currents in the system. The external field $\mathbf{B}_e$ is typically calibrated by considering all interfering fields that are pre-determined through simulation or experimental analysis. However, if changes in the geometry or magnetic properties of the system body occur during operation, the deviations are introduced as an additional current source within the system. This leads to the superposition of an unexpected magnetic field $\mathbf{B}_{iu}$ onto the measured magnetic field, thereby increasing the error in the estimation of the external field as follows:

$$\mathbf{B}_m = \mathbf{B}_e + \mathbf{B}_i + \mathbf{B}_{iu}. \quad (2)$$

The ISC is strategically positioned near the sensing area, using the inherent properties of the ferromagnetic material to generate a magnetic field induced by the surrounding magnetic fields. Its primary objective is to produce a magnetic field that counteracts the interference field while simultaneously preserving the external field. This approach effectively mitigates the influence of unexpected fields superposed on the interference

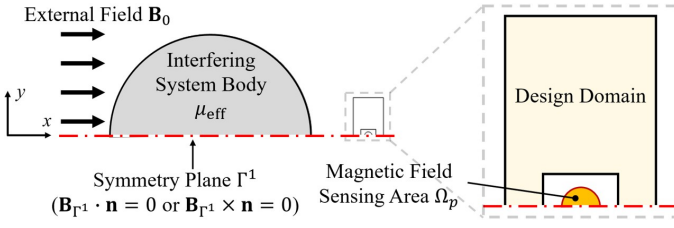


Fig. 1. Configuration of the ISC design problem.

field. Therefore, it is crucial to design the ferromagnetic material of the ISC to meet the conflicting objectives of reducing one magnetic field while preserving another.

III. DESIGN OF THE INTERFERENCE SUPPRESSION CORE

A. Problem Definition

Fig. 1 shows a two-dimensional magnetic system modeled with an effective relative permeability $\mu_{\text{eff}} = 5$, averaging its overall magnetic properties. A uniform magnetic field, denoted as $\mathbf{B}_0$, was applied around the system. The magnetic system estimated the external field using magnetic field measurement data acquired from the sensing area, as shown in Fig. 1. The ISC was positioned within the designated design domain.

The design objective was to minimize the interference field $\mathbf{B}_i$, while preserving the external field $\mathbf{B}_0$. The corresponding objective function to be minimized was formulated as follows:

$$F = \int_{\Omega_p} (|\mathbf{B}_i + \mathbf{B}_{\text{ISC}}^i|^2 + |\mathbf{B}_{\text{ISC}}^e|^2) d\Omega, \quad (3)$$

where $\mathbf{B}_{\text{ISC}}^i$ and $\mathbf{B}_{\text{ISC}}^e$ represent the magnetic fields generated by the ISC, induced by the interfering and external fields, respectively. The objective function was specifically defined to minimize the magnetic field produced by the system body, as well as the magnetic field induced in the ISC by the system body's field, while simultaneously reducing the magnetic field induced in the ISC by the external magnetic field.

B. Optimization Using Continuum Sensitivity Analysis

In this study, the design optimization of the ISC was performed using the design velocity, which was derived from design sensitivity analysis. The design velocity $\mathbf{v}$ assigned to the surface of ferromagnetic materials interfacing with air or an insulator can be obtained using the continuum approach as

$$\mathbf{v} \cdot \mathbf{n} = - \left(1 - \frac{1}{\mu_f} \right) \mathbf{B}(\mathbf{A}_f) \cdot \mathbf{B}(\boldsymbol{\lambda}_a), \quad (4)$$

where $\mathbf{n}$ is the unit normal vector directed outward from ferromagnetic material, μ_f is the permeability of the ferromagnetic material, $\mathbf{B}(\cdot)$ denotes the curl operator, $\mathbf{A}_f$ is the magnetic vector potential on the ferromagnetic material side, and $\boldsymbol{\lambda}_a$ is the adjoint variable defined on the air side [3].

The design velocity for the ISC was formulated to accommodate the multi-objective nature of the optimization as follows:

$$\mathbf{v}_{\text{ISC}} \cdot \mathbf{n} = - \left(1 - \frac{1}{\mu_f} \right) (\mathbf{B}(\mathbf{A}_{f\text{ISC}}^i) \cdot \mathbf{B}(\boldsymbol{\lambda}_a^i) + \mathbf{B}(\mathbf{A}_{f\text{ISC}}^e) \cdot \mathbf{B}(\boldsymbol{\lambda}_a^e)). \quad (5)$$

The superscripts i and e indicate that the corresponding variables are determined in the presence the interfering and external fields, respectively.

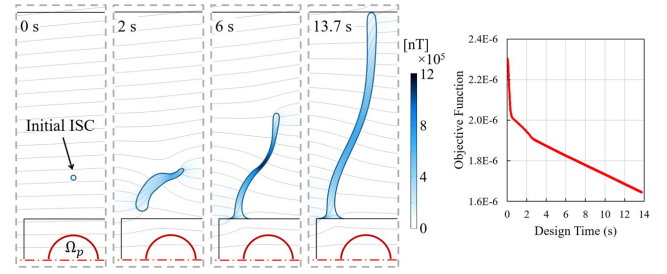


Fig. 2. Design optimization of the ISC under an external field of $50,000\hat{x}$ nT.

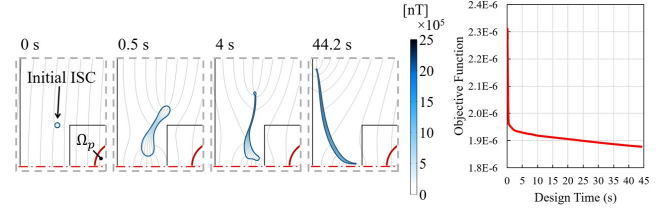


Fig. 3. Design optimization of the ISC under an external field of $50,000\hat{y}$ nT.

C. Results and Discussion

The design process of the ISC began with an initial model comprising a small circle-shaped ferromagnetic material with a relative permeability of 200. Fig. 2 shows the design results under an external field $\mathbf{B}_0$ set to $50,000\hat{x}$ nT. The effectiveness of the optimized ISC model was numerically validated by comparing the magnetic field deviations within the sensing area under varying effective permeability of the system body. For instance, when μ_{eff} decreased from 5 to 4, the magnetic field deviation without the ISC was 1,361 nT. In contrast, with the ISC, the deviation decreased to 1,020 nT, leading to a 25.1 % reduction compared to the case without the ISC. Fig. 3 illustrates the ISC design optimized for an external field of $50,000\hat{y}$ nT. This design achieved a 18.1 % reduction in the magnetic field deviation. These findings highlight the potential of the ISC design to enhance robust field estimation performance in high-resolution measurement scenarios.

IV. CONCLUSION

The design optimization of the ISC has demonstrated its capability to effectively mitigate errors in estimating the target external field, even under system variations during operation that are not fully compensated by conventional error correction methods. Further research will aim to refine the optimization framework to further enhance error reduction performance and broaden its applicability to multi-axis magnetic sensing. Comprehensive findings will be presented at the conference and detailed in the full paper.

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