

Modeling and suppression of magnetic noise in P-N composite magnetic shielding devices

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Magnetic shielding devices (MSDs) can provide high shielding factors (SFs) and low magnetic noise (MN) environments for fundamental physics research, ultra-weak mind-brain magnetic high-resolution imaging, and material magnetic field analysis. To further suppress and calculate MN, we propose a permalloy-nanocrystalline (P-N) composite shielding structure and establish a quantitative calculation model for MN. Validation experiments conducted on the P-N composite MSD show an average error of 5.32% between theoretical and calculated values within the 3-100 Hz range, confirming the accuracy of the proposed calculation method. Compared to the permalloy MSD, the P-N composite MSD achieves a 29.6% reduction in MN. This research not only establishes a theoretical foundation for the design of low magnetic noise magnetic shielding devices but also offers innovative approaches and technical support for optimizing the application of ultra-weak magnetic field measurement systems.

Index Terms—Magnetic shielding, magnetic noise, magnetic properties, power losses

I. INTRODUCTION

DEVICES including ultrasensitive comagnetometer, atomic spin inertial sensors, and biomedical magnetic signal detectors need to operate under low-noise and near-zero magnetic field conditions[1]. Therefore, the reduction of remanence and magnetic noise (MN) inside Magnetic shielding devices (MSDs) is crucial for high sensitivity measurements[2].

MN primarily arises from eddy current losses and hysteresis losses in shielding materials, and its magnitude is influenced by the combined effects of the physical properties of the materials, structural design, and external conditions. In recent years, significant progress has been made in the design of MSDs based on composite structures. By combining materials with different properties, such as integrating permalloy with nanocrystalline alloys, it is possible to effectively enhance shielding performance and reduce MN[3]. However, limited attention has been given to the sources of MN and the mechanisms for its suppression in composite MSDs. To address the above issues, this study proposes the design of MSD based on a P-N composite structure and develops a theoretical calculation model for MN characteristics in the low-frequency range.

II. MAGNETIC NOISE THEORY AND MAGNETIC PROPERTY MEASUREMENT

According to the fluctuation-dissipation theory, the calculation of a material's intrinsic MN can be transformed into solving its power loss. Therefore, MN can be expressed as[4]:

$$\delta B_m(f) = \sqrt{S_B(f)} = \frac{\sqrt{4kT} \sqrt{2P(f)}}{2\pi f A I} \quad (1)$$

where k represents the Boltzmann constant; T denotes the material's absolute temperature, $P(f)$ represents the power loss, A is the surface area of the excitation coil, f indicates the frequency, and I denote the magnitude of the current. The Johnson current noise formula is expressed as follows:

$$\delta B_{eddy}(f) = \frac{\sqrt{4kT} \cdot \sqrt{2P_{eddy}(f)}}{2\pi f A I} = \frac{\sqrt{kT} \int_V \sigma E^2 dV}{\pi f A I} \quad (2)$$

The relationship between Johnson current noise and magnetization noise in symmetrical magnetic shielding measured along its axis can be expressed as[1]:

$$\frac{\delta B_{hyst}(f)}{\delta B_{eddy}(f)} = \sqrt{\frac{P_{hyst}(f)}{P_{eddy}(f)}} = \sqrt{\frac{3\mu_{hyst}''}{2\pi f \sigma \mu^2 t^2}} \quad (3)$$

where t represents the thickness of the MSD, σ denotes electrical conductivity, and μ_{hyst}'' is the imaginary part permeability associated with hysteresis loss. Based on Eqs. (2) and (3), magnetization noise can be expressed as:

$$\delta B_{hyst}(f) = \frac{\sqrt{3kT\mu_{hyst}''}}{\mu t A I \sqrt{2\pi^3 f^3}} \sqrt{\int_V E^2 dV} \quad (4)$$

where $\int_V E^2 dV$ represents the electromagnetic field volume fraction, calculated using ANSYS Maxwell. The total noise can be expressed as:

$$\delta B_{total} = \sqrt{\delta B_{hyst}^2(f) + \delta B_{eddy}^2(f)} \quad (5)$$

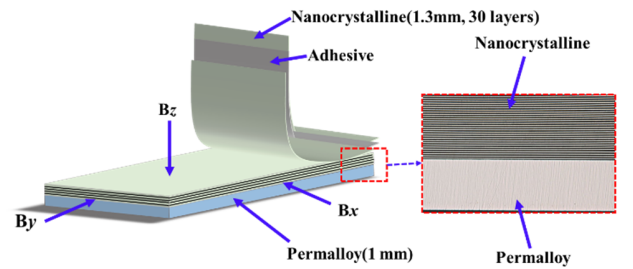


Fig. 1. Schematic diagram of the P-N composite MSD structure.

TABLE I
PARAMETERS OF 1K107 AND 1J85 RING SAMPLES

Material parameters	1K107	1J85
External diameter r_1 (mm)	30	40
Internal diameter r_2 (mm)	20	35
Thickness h (mm)	10	5
Conductivity ($S \cdot m$)	7.6×10^5	1.76×10^6
Stacking factor F_N	0.89	1

The P-N composite MSD is shown in Fig. 1. The test ring and the MSD are made from the same batch of materials, with specific parameters listed in Table 1. The power loss of the permalloy 1J85 and the nanocrystalline alloy 1K107 ring

samples under different frequencies and magnetic field intensities was measured using a soft magnetic material testing system.

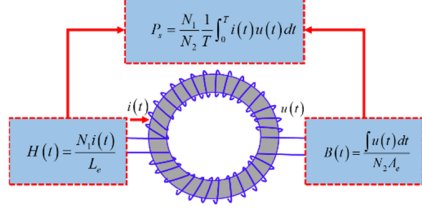


Fig. 2. Schematic diagram of the power loss testing principle.

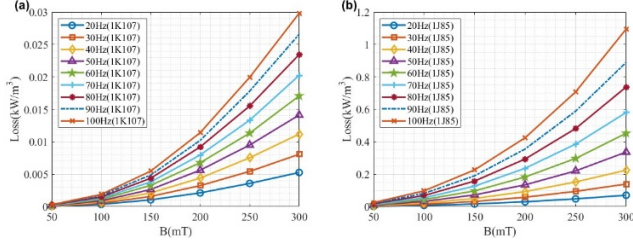


Fig. 3. Power loss characteristics of materials. (a) 1K107; (b) 1J85.

The principle and test results of power loss measurement are shown in Figs. 2 and 3. The magnetization characteristics of 1J85 and 1K107 differ, with 1K107 being more suitable for low-noise shielding in extremely weak magnetic fields. To calculate μ_{hyst}'' , the Bertotti loss separation method is applied to 1K107 for loss decomposition, and the results are shown in Fig. 4.

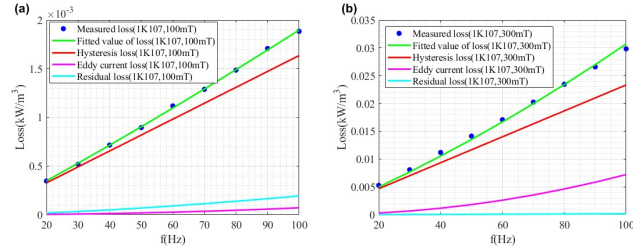


Fig. 4. Loss separation results of 1K107 based on the Bertotti model. (a) 100 mT; (b) 300 mT.

Using the calculation relationship $P_{hys}(f) = \int_V \pi f \mu_0 \mu_{hyst}'' H^2 dV$, the variation trend of μ_{hyst}'' with the magnetic field can be obtained, which is used for calculating MN. The fitted μ_{hyst}'' under near zero field is shown in Fig. 5 (b).

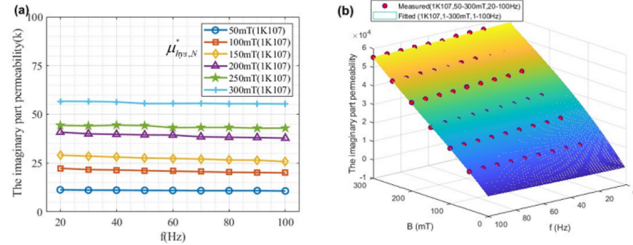


Fig. 5. (a) Imaginary permeability μ_{hyst}'' associated with hysteresis loss; (b) Fitting results of μ_{hyst}'' under near-zero magnetic fields.

III. EXPERIMENT AND ANALYSIS

A near-zero magnetic environment is a prerequisite for realizing the intrinsic MN of MSD materials. The SF of MSD at 1-100 Hz was tested using a sinusoidal magnetic field with an amplitude of 10000 nT. The testing system for the SF and

MN is shown in Fig. 6, and the SF results are presented in Fig. 7. A near-zero magnetic environment is a prerequisite for measuring the intrinsic MN of materials. The P-N composite MSD achieves a SF of approximately 10^4 and a remanence of about 1.5 nT, meeting the requirements for MN testing.

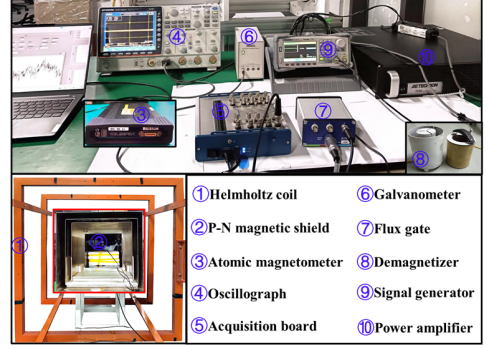


Fig. 6. Testing system for SF and MN of the MSD.

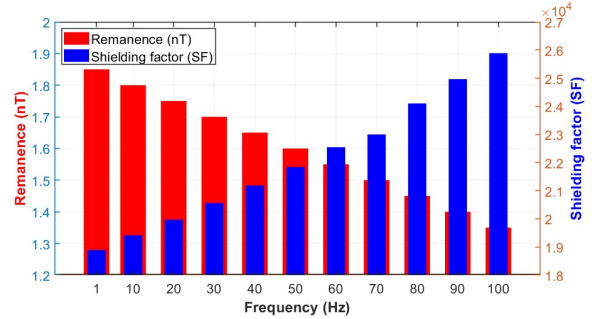


Fig. 7. SF and remanence of the P-N MSD.

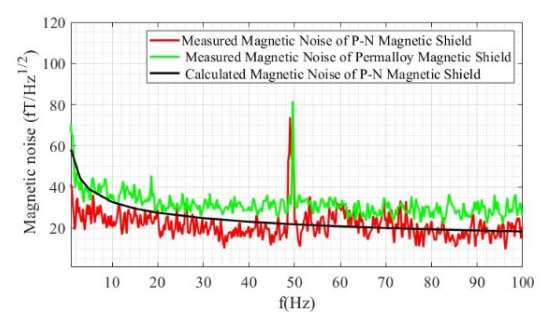


Fig. 8. Comparison and analysis of measured and simulated MN results for the P-N magnetic shielding box.

As shown in Fig. 8, the calculated calculated MN value is $23.33 \text{ fT/Hz}^{1/2}@3\text{-}100\text{Hz}$, while the average experimentally measured MN value is $24.64 \text{ fT/Hz}^{1/2}@3\text{-}100\text{Hz}$, with an average error of 5.32%. Compared to the permalloy shielding box, the P-N shielding box achieves a reduction of approximately 29.6% in the average measured MN.

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