

Magnetic noise analysis and suppression of nanocrystalline spindle-shaped magnetic shielding cylinder

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Nanocrystalline magnetic shielding provides a near-zero magnetic field environment for spin-exchange relaxation-free (SERF) atomic magnetometers, enabling precise measurements of magnetocardiography (MCG) and magnetoencephalography (MEG). Accurate analysis of magnetic noise and its suppression of nanocrystalline magnetic shielding is critical to achieving ultra-high sensitivity in SERF magnetometers. In this study, a magnetic noise model for nanocrystalline spindle-shaped magnetic shielding cylinder (SMSC) considering anisotropy is proposed. Moreover, to more effectively demagnetize the nanocrystalline SMSC to achieve magnetic noise suppression, a segmented dynamic demagnetization model considering anisotropy is proposed.

Index Terms—Anisotropy, demagnetization, magnetic shielding, magnetic noise.

I. INTRODUCTION

Nanocrystalline magnetic shielding provides a near-zero magnetic environment for SERF magnetometers due to its high permeability and low magnetic noise [1]. Common geometries for magnetic shielding include spheres, cylinders, and cubes, with cylinders being the most practical and widely adopted due to their ease of manufacturing. To reduce the size and weight of the cylindrical magnetic shielding, a spindle-shaped magnetic shielding cylinder (SMSC) is used. The SMSC has several advantages over the cylindrical magnetic shielding cylinder (CMSC). With the same axial length, the remanence and magnetic noise of the SMSC are lower than those of the CMSC [2]. Accurately calculating the magnetic noise of a magnetic shielding device is critical. Nanocrystalline is an anisotropic material. However, the existing magnetic noise models for nanocrystalline magnetic shielding primarily address cylindrical or cubic geometries and are not applicable to nanocrystalline SMSC. Furthermore, an effective demagnetization method is critical to ensure that the nanocrystalline SMSC has high magnetic shielding performance and low magnetic noise.

In this study, we propose a magnetic noise model of nanocrystalline SMSC considering anisotropy the structural characteristics. Additionally, to demagnetize the nanocrystalline SMSC more effectively, this study proposes a segmented demagnetization method considering the magnetization characteristics and anisotropy of nanocrystalline.

II. THEORY ANALYSIS

A. Magnetic Noise Model of Nanocrystalline SMSC Considering Anisotropy

The magnetization noise $\delta B_{hyst}(f)$ due to hysteresis losses $P_{hyst}(f)$ and Johnson current noise $\delta B_{eddy}(f)$ due to eddy current losses $P_{eddy}(f)$, respectively [1]. Fig. 1 illustrates the conductivity and permeability analysis of the nanocrystalline SMSC, taking anisotropy into account. When a magnetic field (B_z) is applied in the Z-direction (radial direction), it induces different magnetic field orientations across the nanocrystalline SMSC: vertical on the cylindrical shielding body, and oblique on

the spindle-shaped shielding body, and parallel on the cylindrical shielding cap.

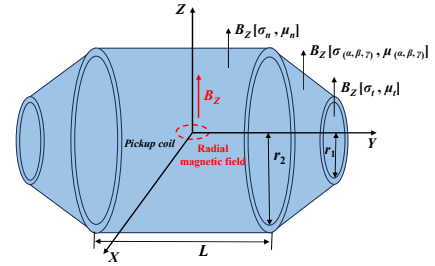


Fig. 1. Analysis of the permeability (μ_t , μ_n) and conductivity (σ_t , σ_n) of the homogenized nanocrystalline SMSC (σ_t and μ_t represent the tangential components, and σ_n and μ_n represent the normal components.).

In Fig. 1, $\sigma_{(\alpha,\beta,\gamma)}$ and $\mu_{(\alpha,\beta,\gamma)}$ denote the effective conductivity and permeability of the nanocrystalline under an oblique magnetic field, which can be derived through spatial transformation. Therefore, the magnetic noise model of the nanocrystalline SMSC considering anisotropy, is as follows:

$$\begin{cases} \delta B_{hyst}(f) = \frac{\sqrt{4kT\sqrt{2P_{hyst}(f)}}}{2\pi fAI} = \frac{\sqrt{2kT\pi\mu_0 f \left(\int_{V_1} \mu_n'' H_m^2 dV_1 + \int_{V_2} \mu_{(\alpha_2,\beta_2,\gamma_2)}'' H_m^2 dV_2 + \int_{V_3} \mu_t'' H_m^2 dV_3 \right)}}{\pi fAI} \\ \delta B_{eddy}(f) = \frac{\sqrt{4kT\sqrt{2P_{eddy}(f)}}}{2\pi fAI} = \frac{\sqrt{kT \left(\int_{V_1} \sigma_n E_m^2 dV_1 + \int_{V_2} \sigma_{(\alpha_2,\beta_2,\gamma_2)} E_m^2 dV_2 + \int_{V_3} \sigma_t E_m^2 dV_3 \right)}}{\pi fAI} \end{cases} \quad (1)$$

where f denotes frequency, k denotes the Boltzmann constant, A denotes the pickup coil surface area, T denotes the Kelvin temperature, μ_0 indicates the vacuum permeability, H_m and E_m indicate the magnetic and electric field strength, μ'' denotes the imaginary part permeability, and E denotes the electric field strength.

B. Segmented Attenuation Demagnetization Model of Nanocrystalline SMSC Considering Anisotropy

To simulate the demagnetization process under the ambient field, the attenuation envelope function with bias is employed as the degaussing field, as follows [3]:

$$H(t) = H_{ac} \sin(2\pi ft) \cdot e(t) + H_{dc} \quad (2)$$

where H_{ac} is the degaussing amplitude, H_{dc} is the bias magnetic field, t is the time, $e(t)$ is the attenuation envelope function.

The dynamic J-A model considering anisotropy can be used as a theoretical basis for optimizing the hysteresis

characteristics and demagnetization waveform shape parameters of nanocrystalline [4].

$$\delta_M \left[\left(\frac{\mu_0^2 d^2 \sigma}{2\beta} \frac{dH}{dt} \right) \left(\frac{dM}{dH} \right)^2 + \sqrt{G\sigma SH_0} \left(\frac{dH}{dt} \right)^{0.5} \left(\frac{dM}{dH} \right)^{1.5} \right] + \left[k\delta - \alpha\delta_M (M_{an} - M) + k\delta\alpha c \frac{dM_{an}}{dH_e} \right] \left(\frac{dM}{dH} \right) - \delta_M (M_{an} - M) + k\delta c \frac{dM_{an}}{dH_e} = 0 \quad (3)$$

where S denotes the cross-sectional area, d denotes the thickness, V_0 refers to the residual loss statistical parameter, G denotes dimensionless constant, a, c, k, α denote characteristic parameter, δ_B and δ_M denote coefficients of J-A model, H_e denotes effective magnetic field strength, M_{an} denotes the anhysteretic magnetization [1]:

$$M_{an} = M_s \frac{\int_0^\pi e^{\frac{E_1(\theta) + E_2(\theta)}{2}} \sin\theta \cos\theta d\theta}{\int_0^\pi e^{\frac{E_1(\theta) + E_2(\theta)}{2}} \sin\theta d\theta} \quad (4)$$

where $E_1(\theta)$ and $E_2(\theta)$ denote anisotropic energy, θ denotes the integration parameter.

As illustrated in Fig. 2(a), the demagnetization effect can be assessed by comparing the deviation ε_B of the actual magnetization state from the ideal anhysteresis state, as represented below [4]:

$$\varepsilon_B = |B_r - B_{dc}| \quad (5)$$

where B_r is the ideal magnetization state corresponding to this bias field, B_{dc} is the remanence at the actual demagnetization under the bias field. To achieve more thorough demagnetization of nanocrystalline materials, this study proposes a segmented attenuation demagnetization method based on the magnetization characteristics of nanocrystalline. Fig. 2(b) illustrates the segmented attenuation demagnetization method using a combination of logarithmic and linear attenuation functions.

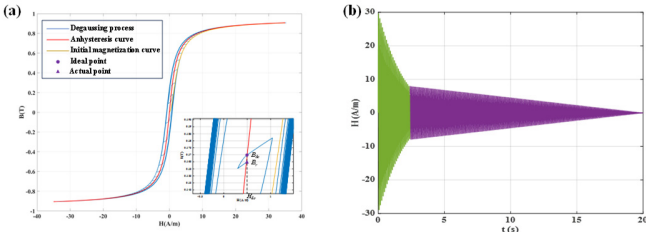


Fig. 2. (a) Changes in the magnetization state of magnetic shielding materials during degaussing processes. (b) The segmented attenuation demagnetization method combining logarithmic and linear decay functions.

The segmented attenuation demagnetization model can be represented by (6).

$$H = \begin{cases} H_{ac1} \sin(2\pi f t_1) \left(b_1 \cdot \ln \left[\frac{T_1(b_2 - b_3) + t_1}{b_3 T_1 - t_1} \right] + b_4 \right) + H_{dc}, & 0 \leq t_1 \leq T_1 \\ H_{ac2} \sin(2\pi f t_2) \left(1 - \frac{t_2}{T_2} \right) + H_{dc}, & T_1 < t_2 \leq T_2 \end{cases} \quad (6)$$

where H_{ac1} and H_{ac2} denote the degaussing amplitude in the reversible and irreversible stages, respectively. t_1 and t_2 denote the time in the reversible and irreversible stages, respectively. T_1 and T_2 denote the total degaussing time in the reversible and irreversible stages, respectively, b_1, b_2, b_3 , and b_4 denote the

parameters of the degaussing field.

III. EXPERIMENTS VERIFICATION AND ANALYSIS

Fig. 3 shows the experimental test platform. Fig. 4 presents the test results for remanence and magnetic noise.

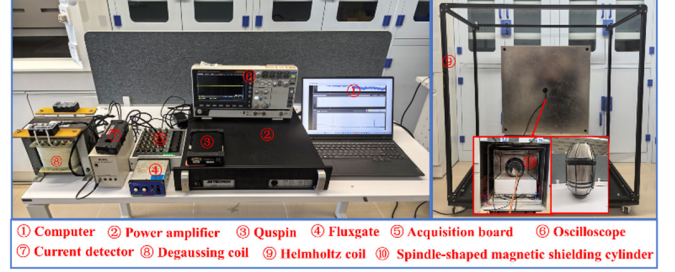


Fig. 3. The experimental test platform.

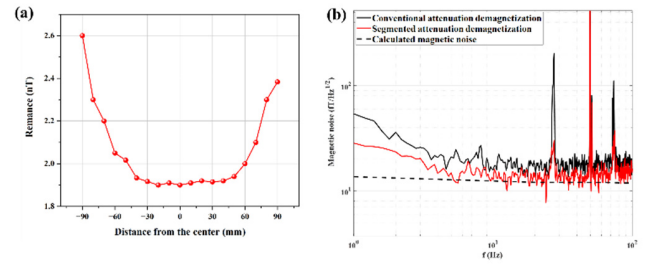


Fig. 4. (a) The remanence in the axial direction of the nanocrystalline SMSC. (b) The magnetic noise under different demagnetization methods.

Conventional demagnetization methods use a single decay function throughout the process [5]. Fig. 4(a) shows the remanence in the axial direction of the nanocrystalline SMSC. The remanence at the center point of the nanocrystalline SMSC is 6.73 nT when using the conventional demagnetization method. The remanence is 2.73 nT when using the segmented decay demagnetization method, resulting in a reduction of 63.24%. The magnetization state significantly influences the magnetic noise. Fig. 4(b) shows the changes in the average magnetic noise of the nanocrystalline SMSC under different demagnetization methods. Compared to the conventional demagnetization method, the segmented attenuation demagnetization method reduced the average magnetic noise of the nanocrystalline SMSC from 18.1 fT/Hz^{1/2} to 14.2 fT/Hz^{1/2} at 1-100Hz, resulting in an improvement in sensitivity of approximately 3.9 fT/Hz^{1/2}. The error between the calculated and measured values of magnetic noise is only 5.42%.

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