Optimization Design on a High-performance Magnetic Shielding Barrel for Atomic Magnetometer Measurement Application

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Abstract. The ultra-high-precision measurement of the atomic magnetometer is largely restricted by the size of its working magnetic field. In order to reduce the residual magnetic field as much as possible, this article carried out the research on the methods to improve the shielding performance. Firstly, the axial shielding factor that limits the shielding performance of the magnetic shielding barrel was derived with various parameters including the radius, length, thickness, number of layers, distance between adjacent layers, etc. of the magnetic shielding barrel. Secondly, simulation was carried out to verify the correctness of the formula. Simulation shows that the shielding performance of the magnetic shielding barrel decreases with the size of magnetic shielding barrel increase. Besides, with the increase of the distance between two adjacent spacing layers, the shielding performance first increases rapidly and then gradually decreases, indicating that the optimal distance between adjacent layers is 9mm. Especially, the performance of the magnetic shielding barrel improves significantly as the layer thickness and number of layers increase. Experimental results show that the internal remanence of the three-layer magnetic shielding barrel is less than 1nT, and the available axial length of homogeneity range is greater than 200mm.

1. Introduction
Atomic Spin Magnetometer has attracted much attention because of its super high theoretical sensitivity [1,2]. It is a magnetic field measuring device based on atomic transitions of ultrafine energy levels and working in a weak magnetic environment [3]. To achieve ultra-high-precision magnetic field measurement, the SERF state of alkali metal atoms must be realized first, which requires a very weak magnetic environment. At present, magnetic shielding barrels are widely used to shield external magnetic fields, and a series of researches on magnetic shielding technology have been carried out. A. Mager [4] gave the shielding coefficient formulas of single and double wall spherical shells and cylindrical shells. T. J. Sumne [5] analyzed the multi-layer cylindrical shield and established the axial total shielding factor model and the radial total shielding factor model, which provided a theoretical basis for the subsequent research on this shielding layer. Papers [6] gave the modeling results of the axial shielding effectiveness of the three-layer cylindrical magnetic shielding device, focusing on the shielding layer spacing, the end cover geometry, the end cover hole and the gap between the mating surfaces for shielding Impact. Zhang H [7] obtained the parameter optimization model of the magnetic shield barrel by improving the axial coefficient formula of the multilayer magnetic shield barrel, and optimized the parameters of the magnetic shield barrel. Li J [8] uses a combination of analytical formula and finite element analysis to study the effect of openings on magnetic shielding performance. Literature [9] uses Ansoft software to study the shielding performance of different combinations of magnetic shielding barrels. Literature [10] used finite element software to simulate and analyzed the relationship between the number of layers of the magnetic shield barrel and the internal remanence under the premise of a certain size. This article comprehensively considers the structure of each parameter of the magnetic shield barrel, derives the axial shielding factor formula of the magnetic shield barrel with multiple parameters, and verifies its shielding performance through simulation and experiment.
2. Principle of Magnetic Shielding

The external magnetic field mainly comes from the geomagnetic field and environmental interference, and the geomagnetic field is the main source of the magnetic field. The total strength of the geomagnetic field is about 50000nT, which can be divided into the main magnetic field and the variable magnetic field. The main magnetic field accounts for about 95%. Environmental interference mainly refers to the magnetic field caused by factors such as electronic equipment and magnetic devices. Therefore, external magnetic field interference can be divided into four categories: static magnetic field, low-frequency alternating magnetic field, high-frequency alternating magnetic field, and electromagnetic waves. Among them, the static magnetic field accounts for the largest proportion.

For the static magnetic field, the main shielding method is flux shunting, and the ferromagnetic shielding shell is mainly used to form a low magnetic resistance path to shunt the magnetic circuit, thereby realizing the shielding of the internal cavity, and the material is required to have high permeability. Since the permeability of high-permeability materials is much greater than that of air, the high-permeability shielding layer is equivalent to a low-reluctance magnetic path to the external magnetic field, and most of the magnetic lines of force will pass through the shielding layer. Only a few magnetic lines of force will enter the inside of the shielding layer to achieve magnetic shielding effect [11]. The principle is shown in Figure 1.

![Figure 1. Schematic diagram of magnetic shielding](image)

The shielding performance of the magnetic shielding barrel can be evaluated by the shielding factor $S$, which can be expressed as:

$$S = \frac{B_1}{B_0}$$  \hspace{1cm} (1)

Where $B_1$ is the uniform external magnetic flux density, $B_0$ is the shielding center magnetic flux density.

According to the different shape and structure, the magnetic shielding layer can be divided into spherical, cylindrical and square. For a single-layer cylindrical magnetic shielding barrel, when the thickness $t$ of the shielding barrel is much smaller than the radius, and the relative permeability of the material is much greater than 1, the axial shielding coefficient is as follows:

$$S_A = \frac{2\mu_r t R^{3/2}}{L^{3/3}}$$  \hspace{1cm} (2)

Where $\mu_r$ is the relative permeability, $t$ is the thickness of the shielding material, $R$ is the average radius and $L$ is the average length.

In actual use, the shielding performance of a single-layer shielding barrel cannot meet the required shielding coefficient, therefore a multi-layer shielding barrel is generally selected to obtain a higher shielding factor. The total radial shielding factor and the total axial shielding factor of the multilayer cylindrical magnetic shielding barrel are shown in formulas (3) and (4) respectively.

$$S_{rT} = S_{r1} \prod_{i=1}^{n-1} S_{ri} \left[ 1 - \left( \frac{R_i}{R_{i+1}} \right)^2 \right]$$  \hspace{1cm} (3)

$$S_{aT} = S_{a1} \prod_{i=1}^{n-1} S_{ai} \left[ 1 - \frac{L_i}{L_{i+1}} \right]$$  \hspace{1cm} (4)

The comparison between $S_{rT}$ and $S_{aT}$ is shown in Figure 2.
Figure 2. Comparison chart of $S_{rT}$ and $S_{aT}$

It can be seen from the figure that the axial magnetic shielding factor is smaller than the radial magnetic shielding factor under the same structural parameters. Therefore, when designing, the influence of the size structure on the axial magnetic shielding factor is mainly considered.

3. Optimization and Simulation Analysis

3.1. Parameter Optimization of Magnetic Shielding Barrel

It can be seen from formula 10 that the shielding performance of the magnetic shielding barrel has a lot to do with its structure, which can be improved by optimizing the structure of the magnetic shielding barrel.

For a three-layer magnetic shielding barrel, the axial magnetic shielding factor is as follows.

$$S_{aT} = S_{a3} \prod_{i=1}^{2} S_{ai} \left[ \frac{1 - \frac{L_i}{L_{i+1}}} \right] = S_{a3} S_{a2} S_{a1} \left( \frac{1 - \frac{L_1}{L_2}} \right) \left( \frac{1 - \frac{L_2}{L_3}} \right)$$  \hspace{1cm} (5)

Substituting formula (2) into formula (5) can obtain the optimization formula (6) of the axial magnetic shielding factor of the magnetic shielding barrel including each parameter.

$$S_{az} = 8 \mu_r \mu_r \mu_r t_1 t_2 t_3 \frac{R_1 R_2 R_3 (L_2 - L_1)(L_3 - L_2)}{L_1^2 L_2^2 L_3^2}$$  \hspace{1cm} (6)

In order to facilitate calculation, set the axial layer spacing=radial layer spacing=DL, $t_1=t_2=t_3=T$, and the materials of each layer are the same. Equation 6 can be written as:

$$S_{az} = 8 \mu_r t \frac{DL \sqrt{R_1^2 + 3R_2^2DL + 2R_3^2DL^2}}{L_1^2 L_2^2 L_3^2}$$  \hspace{1cm} (7)

Figure 3. The relationship curve between $S_{az}$ and R, L, T, DL

It can be seen from Equation (7) that the axial shielding factor is related to the length of the innermost layer, the radius of the innermost layer, the layer spacing, and the thickness. Keeping the other parameters unchanged, the relationship curve between each parameter and the axial magnetic shielding factor can be obtained as figure 3 by only changing a single parameter.

As can be seen from figure 3, the innermost layer radius, innermost layer length, thickness, and layer spacing have a greater impact on the total axial shielding coefficient. The thickness has the most significant effect. The larger the thickness, the better the shielding effect. The smaller the inner layer size, the better the
shielding effect, and the curve of DL and the axial magnetic shielding factor has an obvious maximum value. The closer the DL is to the maximum point, the better the shielding effect. According to the above analysis, the magnetic shield barrel can be optimized design.

3.2. Finite Element Simulation

Four magnetic shielding barrels labeled 1, 2, 3, 4 are designed, and their parameters are shown in the table 1.

| Number | 1   | 2   | 3   | 4   |
|--------|-----|-----|-----|-----|
| Number of layers | 3   | 2   | 3   | 2   |
| Inner radius/mm   | 100 | 100 | 120 | 130 |
| Inner length/mm   | 400 | 400 | 450 | 500 |
| Thickness/mm      | 1   | 1   | 1   | 1   |
| Layer spacing/mm  | 9   | 9   | 9   | 9   |

Permalloy is widely used in static magnetic field shielding because of its relative permeability can reach $10^4$–$10^5$, which is much higher than common ones. Among them, 1J85 has the highest initial permeability and saturation permeability. Therefore, this article chooses 1J85 as the simulation material. The B-H curve of the material used is shown in Figure 4.

The Finite element simulations are conducted to simulate the performance of the magnetic shielding barrel. The figure 5 shows the magnetic shielding barrel model. In order to facilitate light passing and routing, light passing holes and routing slots are designed. The simulation conditions follow the local magnetic field size: north-south direction: 26344.4 nT; sky-earth direction: 42424.2 nT; east-west direction: -2482.4 nT.

It can be clearly seen from the table that increasing the number of layers can increase the magnetic shielding effect by an order of magnitude. With the same number of layers, the smaller the volume, the better the shielding effect.

The simulation results are shown in Table 2:
Table 2. Simulation of residual magnetism inside the magnetic shielding barrel

| Distance/mm | 1/nT | 2/nT | 3/nT | 4/nT |
|------------|------|------|------|------|
| 50         | 0.226| 27.507| 1.852| 9.516|
| 100        | 0.264| 7.157| 0.407| 10.890|
| 150        | 0.267| 7.623| 0.433| 11.521|
| 200        | 0.294| 7.905| 0.457| 11.993|
| 250        | 0.302| 7.948| 0.459| 12.210|
| 300        | 0.291| 7.675| 0.444| 12.153|
| 350        | 0.266| 7.333| 0.488| 11.765|
| 400        | 0.211| 20.943| 0.359| 11.753|

4. Experimental Verification

In order to verify the correctness of the theory and simulation, we processed two magnetic shielding barrels No. 1 and No. 4, and tested the internal remanence and uniformity.

Figure 6. Test experiment of residual magnetism inside magnetic shielding barrel

The test data are as follows:

Table 3. Test data of residual magnetism inside magnetic shielding barrel

| Distance/mm | 1/nT | 4/nT |
|------------|------|------|
| 0          | 1.15 | -17.4|
| 50         | 0.10 | -16.9|
| 100        | -0.11| -15.15|
| 150        | -0.35| -15.05|
| 200        | -0.55| -15.65|
| 250        | -0.83| -16.45|
| 300        | -1.25| -16.65|
| 350        | -3.65| -17.75|
| 400        | -5.67| -20.15|

It can be seen that the internal remanence of barrel 1 is less than 1nT in the range of 50mm-250mm from the bottom of the barrel, which is consistent with the simulation results. However, the direction of the magnetic field has changed in the range of 50mm to 100mm which is caused by magnetism, in fact, this phenomenon can be eliminated by demagnetization. The internal remanence of barrel 4 is between -15nT - -18nT, which is about 6nT larger than the simulation data. This is because we chose a permalloy with poor permeability during processing. The remanence of the two barrels near the lid of the barrel has a significant increase which obviously is caused by the magnetic leakage generated by the light hole and the wire groove.

5. Conclusion

In this paper, various factors affecting the axial shielding factor of the magnetic shielding barrel are comprehensively considered, and the optimization formula of the parameters of the magnetic shielding barrel is derived. Through simulation and experiments, it is found that increasing the number and thickness of the magnetic shielding barrel can effectively increase the shielding performance of the magnetic shielding barrel, and in the case of the same layer thickness, appropriately reducing the size of the magnetic shielding barrel can increase the magnetic The shielding effect of the shielding barrel, in addition, the selection of materials
with high magnetic permeability can greatly reduce the remanence of the shielding cavity.

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7. References
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