Self-Compensation of the Residual Field Gradient in Double-Shell Open-Ended Cylindrical Axial Magnetic Shields

E. Paperno, I. Sasada, and H. Naka

Dept. of Applied Science for Electronics and Materials, Kyushu University, 6-1 Kasuga-koen, Kasuga-shi, Fukuoka 816-8580, Japan

***Abstract*—An important and not-obvious demonstration made in this work is that replacing a closed double-shell axial cylindrical shield with a similar but open-ended shield can lead to an increasing in not only the axial shielding factor, but in the residual magnetic field uniformity as well. It is shown that a self-compensation of the residual field gradient and a significant improvement of the total residual field uniformity are potentially possible by combining two open-ended cylindrical shells having different length-to-diameter ratios and providing opposite signs and appropriate magnitudes of the residual field gradients. A numerical example confirms the applicability of the method. It is shown that an ~6-fold reduction of the residual field gradient along the axial direction and an ~2-fold reduction of that along the radial direction over a relatively wide area inside a double-shell cylindrical axial shield are possible if its both ends are open.**

***Index Terms*—Magnetic shielding, open-ended cylindrical shields, uniformity, self-compensation.**

I. Introduction

The essential features required of magnetic shields are a large attenuation ratio of external field (large shielding factor) and a low gradient (high uniformity) of the residual field. The ease of the shields fabrication and operation are important factors as well.

The practice demonstrates that open-ended cylindrical shields match well most of the above requirements. Open cylinders can be fabricated relatively easily due to their simple geometry, and their operation is convenient due to an easy access to the shielded area. It is also well known that relatively long, slender *open-ended* cylindrical shields provide a larger axial shielding factor compared to that of similar but completely *closed* cylinders [1].

It is generally assumed, however, that *open-ended* axial cylindrical shields provide an inferior residual magnetic field uniformity compared to that provided by *closed* axial cylindrical shields. The main objective of the present work is to demonstrate that such assumption is not always true; especially in the case of double-shell axial cylindrical shields.

Our primary aim is to show that a properly designed *open-ended* double-shell axial cylindrical shield can provide better uniformity of the residual magnetic field than a similar but completely *closed* shield.

II. Method

The main idea of the present work is based on the two following facts:

- axial magnetic field components penetrating into an open-ended cylinder, one through the openings and another through the shell (see Fig. 1 (a)), have opposite effects on the gradient of the total residual magnetic field at the cylinder's center;
- by extending the length of the cylinder, the effect of the field component entering through the openings is reduced whereas the effect of another field component penetrating through the shell is increased [1], [2].

As a result, the total residual field gradient can be either positive or negative depending on the cylinder's length-to-diameter ratio, L/D, permeability, μ, and thickness, t (see Fig. 1 (b)). Hence, it is potentially possible to compensate the total residual field gradient and to improve the uniformity of the residual field by combining two or more open-ended cylindrical shells having different length-to-diameter ratios and providing opposite signs and appropriate magnitudes of the residual field gradients.

It is important to note that according to [3], the adjustment of the shells' lengths, which is necessary for the compensation of the total residual field gradient, is expected to be sufficiently small to cause no serious reduction in the axial shielding factor. Fig. 2 [3] shows that the $(L/D)_{unif\,opt}$ ratios corresponding to minimum values of the residual field gradient (approximated by the dashed line) are nearly equal to the $(L/D)_{opt}$ ratios corresponding to maximum values of the axial shielding factor (approximated by the dashed-dotted line). It is also shown in [3] that in the regions at the left and

Manuscript received March 5, 1999.

E. Paperno, Tel/Fax: +81-92-583-7596, Fax: +81-92-583-7677, e-mail: paperno@ence.kyushu-u.ac.jp; I. Sasada, Tel: +81-92-583-7594, Fax: +81-92-583-7677, e-mail: sasada@ence.kyushu-u.ac.jp; H. Naka, Tel/Fax: +81-92-583-7596, Fax: +81-92-583-7677, e-mail: h-naka@ees.kyushu-u.ac.jp.

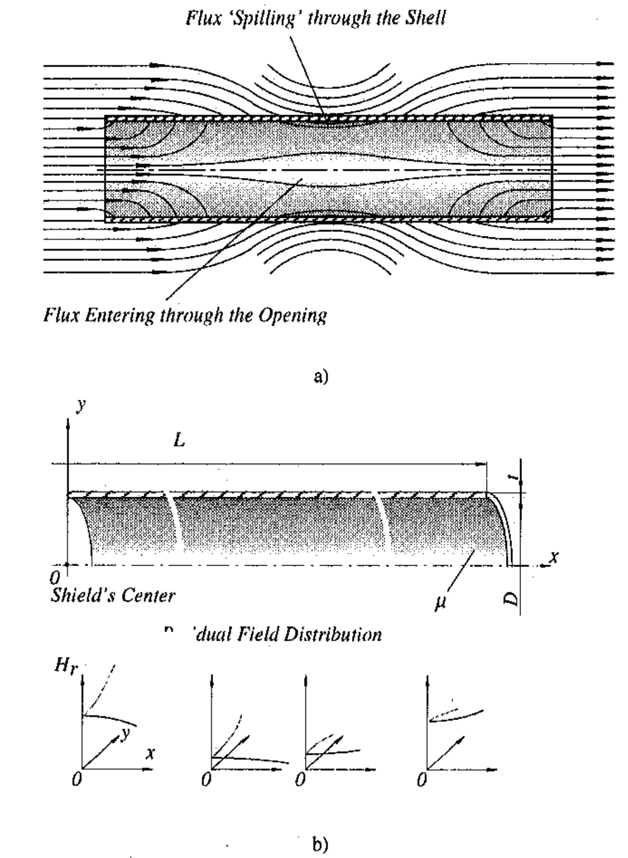

Fig. 1. Residual magnetic field distribution inside open-ended axial cylindrical shields.

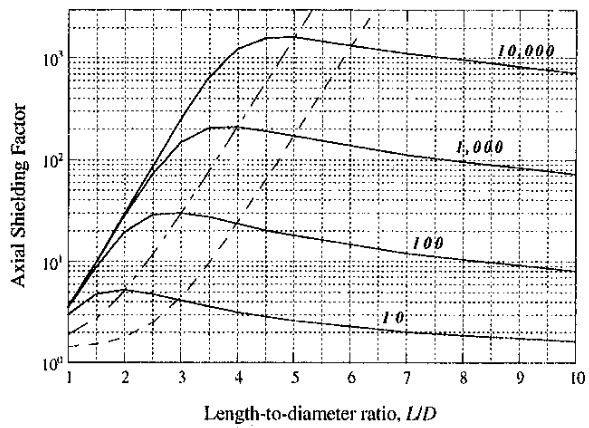

Fig. 2. Dependencies of the axial shielding factors of single-shell open-ended cylindrical shields on the shields' length-to-diameter ratio, L/D=1...10, and normalized permeability, $\mu t/D$=**10**; **100**; **1,000**; **10,000**. The dashed line approximates values of the $(L/D)_{unif\,opt}$ ratios that provide minimum gradient (maximum uniformity) of the residual field. In the regions at the left and right of this line, residual field gradients have opposite signs. The dashed-dotted line approximates values of the $(L/D)_{opt}$ ratios corresponding to maximum values of the axial shielding factor.

right of the dashed line in Fig. 2, residual field gradients have opposite signs; and small deviations from the $(L/D)_{unif\,opt}$ values cause a relatively large increase in the residual field gradient.

III. Numerical Example

Results of numerical calculations support the main idea of the present work. Consideration was given to the following example of a numerical model (see Fig. 3), where L_2/D_2=5, D_1/D_2=0.8, t_1=t_2=1% of D_2, and μ=10,000 are constant parameters and the L_1/L_2 is a variable.

Fig. 4 (a), (b) show the axial and radial gradients of the residual magnetic field calculated separately for the inner and outer shells. One can see that a shorter inner shell provides an opposite sign of the residual field gradient compared to that provided by a longer outer shell. Moreover, by elongating the inner shell from L_1/L_2=0.4 to L_1/L_2=0.6, magnitudes of the field gradients approach nearly equal values.

Fig. 4 (c), (d) show that combining the two shells into a double-shell shield allows one to compensate the gradient of the total residual field. An optimum value of the L_1/L_2 ratio can be apparently chosen as 0.5<L_1/L_2<0.6. It should be considered, however, that increasing the L_1/L_2 ratio beyond L_1/L_2=0.4 leads to a decreasing axial shielding factor [4]: S_a≈221, 186, 145 for L_1/L_2=0.4, 0.5, 0.6 (see Fig. 5).

It is important to observe in Fig. 4 (c), (d) that in the

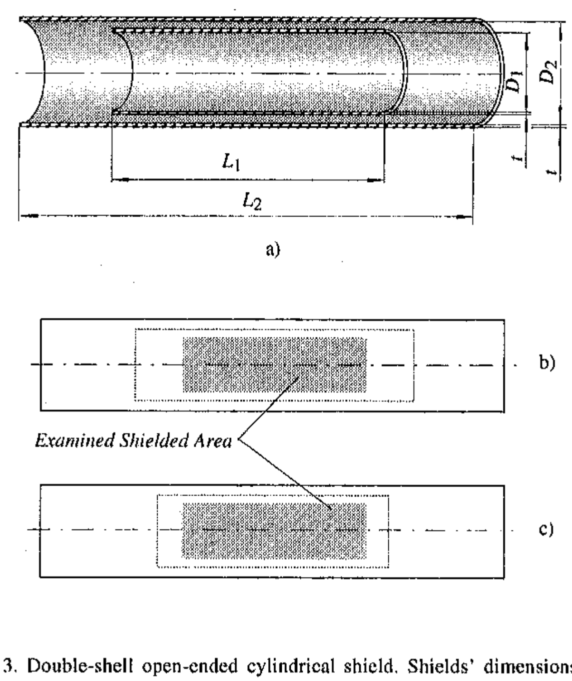

Fig. 3. Double-shell open-ended cylindrical shield. Shields' dimensions: L_2/D_2=5, D_1/D_2=0.8, t_1=t_2=0.01·D_2, μ_1=μ_2=10,000, b) L_1/L_2=0.6, c) L_1/L_2=0.5. Examined shielded area: L_a= 2·D_2, D_a=0.6·D_2.

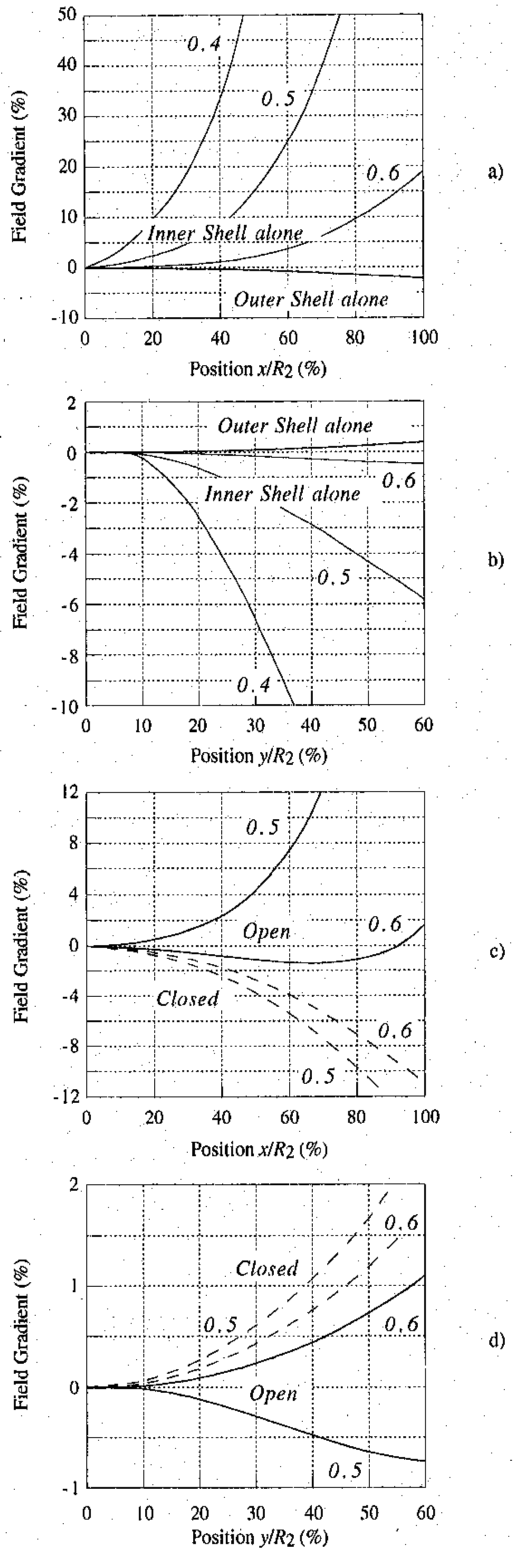

Fig. 4. Residual magnetic field gradients a), b) for a single-shell and c), d) for double-shell open-ended axial cylindrical shields. The gradients a), c) are measured along the axis [see Fig. 1 (b)] and b), d) are measured along the radius and are normalized to the field magnitude at the center of the shields. (Numbers in the figure show the L_1/L_2 ratio.)

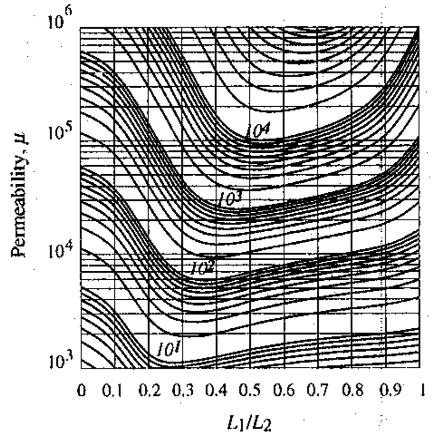

Fig. 5. Axial shielding factor of double-shell open-ended cylindrical shield as a function of the inner shell to outer shell lengths ratio, L_1/L_2, and permeability. L_2/D_2=5, D_1/D_2=0.8, t_1=t_2=0.01·D_2. [4].

examined shielded area (see Fig. 3 (b), (c)), an *open-ended* cylindrical shield with L_1/L_2=0.6 provides better uniformity of the residual magnetic field than can be achieved with a similar but completely *closed* shield (S_a=141).

IV. CONCLUSIONS

It is demonstrated that a properly designed *open-ended* double-shell axial cylindrical shield can provide better uniformity of the residual magnetic field than a similar but completely *closed* magnetic shield. Numerically obtained results show that a self-compensation of the total residual field gradient and a significant improvement in the uniformity of the residual field are potentially possible by combining two open-ended cylindrical shells having different length-to-diameter ratios and providing opposite signs and appropriate magnitudes of the residual field gradients.

An important and not-obvious conclusion made in this work is that replacing of relatively long, slender double-shell *closed* cylinders with similar but *open-ended* shields can lead not only to an increasing in the axial shielding factor but also to an enhancement in the residual magnetic field uniformity.

REFERENCES

[1] A. Mager, "Magnetic shields," *IEEE Trans. Magn.*, vol. 6, pp. 67–75, 1970.

[2] A. Mager, "Das eindringen von magnetfeldern in offene abschirmzylinder," *Z. Angew. Phys.*, vol. 23, pp. 381-386, 1967.

[3] E. Paperno, I. Sasada, and H. Naka, "Optimum axial efficiency of open cylindrical magnetic shields," submitted for publication to *IEEE Trans. Magn.*

[4] E. Paperno, "Charts for estimating the axial shielding factors of open-ended cylindrical shields ," submitted for publication to *IEEE Trans. Magn.*