Magnetic shielding properties of sheet metal products taking into account hysteresis effects

Peter Sergeant, a) Luc Dupré, and Lode Vandenbossche

Department of Electrical Energy, Systems and Automation, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium

Marc De Wulf

Arcelor—Ocas, JF. Kennedylaan 3, B-9060 Zelzate, Belgium

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Analytical expressions are presented to find the shielding effectiveness and the losses of a shield consisting of ferromagnetic, isotropic, nonlinear, and hysteresic material, characterized by the Preisach distribution function in the Rayleigh region. The nonlinear shield is divided into a sufficient number of piecewise linear sublayers with a permeability that is constant (space independent) and complex (to model hysteresis). Simulations of an infinitely long cylindrical shield in transverse sinusoidal flux show that the shielding of perfectly linear material is better than the one of nonlinear metal sheets. More hysteresis and nonlinearity deteriorate the shielding factor, as eddy current losses decrease. © 2005 American Institute of Physics. [DOI: 10.1063/1.1850380]

I. INTRODUCTION

In order to design a good magnetic shield for a given shielding problem, one wants to compare several materials concerning their shielding effectiveness and electromagnetic losses. In this article, fast analytical expressions are presented for the shielding effectiveness of multilayered shields consisting of nonlinear material with given Preisach distribution. Simulation results are shown to reveal the influence of nonlinearity and hysteresis on a cylindrical steel shield with an experimentally determined Preisach distribution.

II. SHIELDING FACTOR OF LINEAR MATERIALS

In this article, a bar on top of a symbol means a space vector $\vec{X}$ and an underlined symbol indicates a time phasor, a complex representation of a quantity that varies sinusoidally in time: $X = X \sin(\omega t)$. The shielding factor in a point is defined as $|H_s|/|H_0|$ with $H_s$ the magnetic field with the shield present and $H_0$ the magnetic field in the same point without shield. To calculate the shielding factor, we use the analytical expressions presented in Ref. 2. We apply them to an infinitely long cylindrical shield in a transverse magnetic field. Figure 1(a) shows Hoburg’s geometry of the shield that consists of several layers of linear materials. Far from the shield, the magnetic field is the uniform transverse imposed field $H_0$. Layer $l$ has thickness $d_l$, conductivity $\sigma_l$ and constant permeability $\mu_l$. Its outer surface is labeled $\beta$ and its inner surface is $\alpha$.

To obtain easier expressions, the problem is converted to Hoburg’s planar geometry in Fig. 1(b). In this “unwrapped” version of Fig. 1(a), the magnetic field source is a sheet of surface current that varies sinusoidally with wavelength $\lambda = 2\pi r_i = 2\pi/k$. This conversion avoids the use of Bessel functions—see expressions in Ref. 2—and the corresponding numerical overflow.

In Ref. 2, transfer relations connect electromagnetic values at side $\alpha$ of a layer to the values at the other side $\beta$.

$$\begin{bmatrix} H^a_x \\ B^a_y/\mu_0 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} H^\beta_x \\ B^\beta_y/\mu_0 \end{bmatrix},$$

(1)

where the coefficients $T_{ij}$, $1 \leq i,j \leq 2$ are dependent on the geometry and the material properties of the shield. Starting from an initial field $H_0$, we obtain expressions for the tangential component of $\vec{H}$ and for the normal component of $\vec{B}$ ($\gamma = 0$ on surface $\beta$)

$$H_x = \frac{\eta}{\mu} [A_x \cosh(\eta y) + A_c \sinh(\eta y)] \cos(ky),$$

$$B_x = k[A_x \sinh(\eta y) + A_c \cosh(\eta y)] \sin(ky),$$

(2)

with $\eta = \sqrt{k^2 + \gamma^2}$ with $\gamma = \sqrt{\omega \mu_0 \sigma_l}$. $A_x$ and $A_c$ are constants depending on $H_0$ and the material properties of the layer. $H_x$ and $B_x$ were chosen because they are continuous in adjacent material layers.

Figure 1. (a) A multilayered cylindrical shield. The magnetic field is a uniform transverse field and (b) a multilayered planar shield. The magnetic field is imposed by a sinusoidally distributed source.

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a) Electronic mail: peter.sergeant@ugent.be

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The shielding factor for the whole shield is calculated by splicing together the transfer relations (1) of all layers as explained in Ref. 2. As all materials are linear, the shielding factor does not depend on the imposed field $H_0$.

III. SHIELDING FACTOR OF NONLINEAR Hysteretic MATERIALS

A. Preisach model

In many shielding situations, the magnetic field in (a major part of) the shield is weak enough to assume that the working conditions are in the Rayleigh area. For materials exhibiting hysteresis, $b(t)$ is not merely a function of $h(t)$, but of its history as well. Usually, $b(t)$ is split into a reversible part $b_{rev}[h(t)]$ and an irreversible part $b_{irr}[h(t), h_{pa}(t)]$. To present the latter, the classical Preisach model is used.\(^3\) In this article, we choose $b_{rev}(t) = c_1 h(t)$ and the Preisach distribution function $P(\alpha, \beta) = c_2$. Hence, the ascending and descending branch of the hysteresis loop are given by

$$b_{desc}[h(t)] = c_1 h(t) + c_2 h_m^2 - \frac{c_2}{2} [h(t) - h_m]^2,$$

between the extremal values $h_m$ and $-h_m$. The quadratic expressions (3) represent repeatable hysteresis loops in the Rayleigh area. As in this article only shielding situations with weak fields in the Rayleigh region are considered, this choice for $b_{rev}$ and $P(\alpha, \beta)$ is acceptable if we start with demagnetized shielding material: See the experimental verification in Fig. 2.

For a sinusoidal magnetic field, the hysteresis loop described by Eq. (3) gives rise to a non-sinusoidal time variation of $b(t)$. In order to evaluate the shielding efficiency of the nonlinear hysteretic material, we consider only the fundamental component $B'$ of the nonsinusoidal $b(t)$ by using a Fourier analysis (Fig. 2). $B'$ and the corresponding component $\mu'$ of the permeability are

$$B' = \left[ (c_1 + c_2 |H|) - \frac{4}{3 \pi} c_2 |H| \right] H,$$

$$\mu' = \frac{B'}{H} = (c_1 + c_2 |H|) - \frac{4}{3 \pi} c_2 |H| = \mu_s + j \mu_i.$$

B. Procedure

In order to take into account the nonlinear hysteretic material behavior, the shield is divided into fictitious linear sublayers [Fig. 1(b)]. Each fictitious sublayer $p$ has a constant but complex $\mu_p = \mu[H(y_p)]$, calculated with Eq. (4), $c_1$ and $c_2$ in Eq. (4) are the same for all sublayers and $H(y_p)$ is the magnetic field at the source side of sublayer $p$.\(^9\)
μ must be determined in every sublayer. It is replaced by μ′ and calculated by using Eq. (4), which needs H as input value. Here, some approximations are unavoidable, because the analytical algorithm accepts only one μ' per sublayer while the real μ' differs from point to point. (1) The x dependence of \( H_x \sim \cos(kx) \) and \( B_z \sim \sin(kx) \)—see Eq. (2)—is taken into account by taking the rms value (divide by \( \sqrt{2} \)). (2) The y dependence is “discretized” by the sublayers, each having its own μ′, \( p = 1, \ldots, n \). (3) The space vector \( \vec{H} \) in the \( x, y \) plane is taken into account by calculating both \( \mu'(H_x/\sqrt{2}) \) and \( \mu'(H_y/\sqrt{2}) \) and averaging them.

Since \( \mu'_i \) nor \( H \) are known in the sublayers, the problem has to be solved iteratively. First, \( \mu'_i \) is calculated for every sublayer \( p = 1, \ldots, n \) by evaluating Eq. (4) with \( H_0 \) as input argument. After calculating the shielding factor using the calculated \( \mu'_i \), the distribution of \( H \) in the shield is found from Eq. (2), and the \( \mu'_i \) are updated. Iteratively, the \( H \) and the \( \mu'_i \) are updated until the procedure converges. Contrary to the linear case, the shielding factor depends on \( H_0 \).

C. Eddy current losses

With \( \vec{H} \) known from Eq. (2) in each sublayer \( p \), we find the current density \( \vec{J} \) by \( \vec{J} = \nabla \times \vec{H} \). In the cylindrical shield, the eddy current losses \( P_{ec} \) per meter length in the \( z \) direction are

\[
P_{ec} = \frac{1}{2} \sum_{p=1}^{n} \int_{0}^{\lambda} dx \int_{\gamma_p} \frac{|J(x,y) \cdot J^*(x,y)|}{\sigma_p} dy
\]

\[
= \sum_{p=1}^{n} \frac{\omega \pi \sin(\angle \mu'_i)}{8k|\mu'_i|} \left\{ 2 \Re \left[ A_{cp}^* A_{cp}^* \left( k^2 - |\eta_p|^2 \right) \cosh(2j \eta_p d_p) - 1 \right] + \frac{1}{j \eta_p} \right\} + \left( |k A_{cp}^2| + |\eta_p A_{cp}^2| \right) \left[ \frac{\sinh(2j \eta_p d_p)}{\eta_p} - \frac{\sinh(2j \eta_p d_p)}{j \eta_p} \right] + \left( |k A_{cp}^2| + |\eta_p A_{cp}^2| \right) \left[ \frac{\sinh(2j \eta_p d_p)}{\eta_p} + \frac{\sinh(2j \eta_p d_p)}{j \eta_p} \right] \right\},
\]

D. Hysteresis losses

The power dissipated by hysteresis per meter length is

\[
P_{hy} = \frac{1}{2} \sum_{p=1}^{n} \int_{0}^{\lambda} dx \int_{\gamma_p} \Re \left[ H(x,y) \cdot j \omega B''(x,y) \right] dy
\]

\[
= \sum_{p=1}^{n} \frac{\omega \pi \sin(\angle \mu'_i)}{8k|\mu'_i|} \left\{ 2 \Re \left[ A_{cp} A_{cp}^* \left( k^2 - |\eta_p|^2 \right) \cosh(2j \eta_p d_p) - 1 \right] + \frac{1}{j \eta_p} \right\} + \left( |k A_{cp}^2| + |\eta_p A_{cp}^2| \right) \left[ \frac{\sinh(2j \eta_p d_p)}{\eta_p} - \frac{\sinh(2j \eta_p d_p)}{j \eta_p} \right] + \left( |k A_{cp}^2| + |\eta_p A_{cp}^2| \right) \left[ \frac{\sinh(2j \eta_p d_p)}{\eta_p} + \frac{\sinh(2j \eta_p d_p)}{j \eta_p} \right] \right\}.
\]

Here, the asterisk symbolizes the complex conjugate, \( \eta_p \) is the real part of \( \eta \) in sublayer \( p \) while \( \eta^*_p \) is the imaginary part. Every shield sublayer \( p \) ranges in the \( y \) direction from \( y_p \) to \( y_{p+1} \), having thickness \( d_p \). For every shield sublayer, \( A_{cp} \) and \( A_{cp}^* \) can be calculated by Eq. (2), as \( H_x \) and \( B_z \) are known once Sec. III B is executed.

IV. SIMULATION RESULTS

Figure 3 shows the shielding factor of a cylinder in steel with \( r = 0.3 \) m radius, \( \sigma = 8.5 \times 10^6 /\Omega \) m and complex permeability in the Rayleigh area (4) with \( c_1 = 168.3 \mu_0 \) and \( c_2 = 18.4 \mu_0 \) (values of Magnetil–Arcelor). The imposed source field \( \vec{H}_0 \) is at a large distance from the shield 10 A/m. This low field ensures that the magnetization is in the Rayleigh area. By neglecting the imaginary part of \( \mu' = \mu_1(\vec{H}) \), the shielding factor is slightly worse. Choosing a constant \( \mu'_i \) = \( \mu_1(\vec{H}_0) \) in Eq. (4) results in an overestimation of the shielding efficiency.

Figure 4 shows the shielding factor and the total losses (5) + (6) for a 1 mm thick cylinder with the same \( r \), \( \vec{H}_0 \), and material properties as in Fig. 3. In order to evaluate this analytical approach, the results for the presented model are compared with CPU time consuming finite element (FE) calculations. The correspondence with the FE calculations is acceptable up to 10 kHz. Here, the FE mesh becomes too coarse to accurately model the small skin depth.

When varying the parameters \( c_1 \) and \( c_2 \) in Eq. (4) such that \( \mu_1(\vec{H}_0) \) is constant, more hysteresis and nonlinearity (\( c_1 \) lower and \( c_2 \) higher) in the Rayleigh area deteriorate the shielding factor, but cause less total electromagnetic losses (increase of \( P_{hy} \) and decrease of \( P_{ec} \)). The reason is that with \( c_1 \) lower and \( c_2 \) higher, \( |\mu'| \) decreases faster inside the shield.