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# Influence of frequency of the excitation magnetic field and material's electric conductivity on domain wall dynamics in ferromagnetic materials

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ABSTRACT

The present work analyzes the influence of electric conductivity on the Magnetic Barkhausen Noise (MBN) signal using a microscopic model which includes the influence of eddy currents. This model is also implemented to explain the dependence of MBN on the frequency of the applied magnetic field. The results presented in this work allow analyzing the influence of eddy currents on MBN signals for different values of the material's electric conductivity and for different frequencies of applied magnetic field. Additionally, the outcomes of this research can be used as a reference to differentiate the influence of eddy currents from that of second phase particles in the MBN signal, which has been reported in previous works.



## 1. Introduction

The Magnetic Barkhausen Noise (MBN) [1,2] is a phenomenon produced by the interaction of the moving magnetic domain walls with the micro-structural defects in ferromagnetic materials and is perceived as discontinuous fluctuation in the material magnetization. The MBN depend on a variety of microstructural parameters such as grain size, second phase particles, and residual stress, among others which stimulates the development of MBN-based non-destructive applications for evaluation of carbon content, grain size, plastic deformation [3–8] among others. Additionally, there are other factors that influence the MBN activity and that have only been partly studied, such as the eddy currents produced in the material during the MBN. Eddy currents affect domain wall motion, and the absorption of MBN electromagnetic waves. Also, the eddy currents determine the penetration depth of an applied magnetic field. Until now, there are a few studies about the influence of the eddy currents on MBN signals. In particular, there are a few experimental reports and theoretical studies [9] about the influence of the electric conductivity on the MBN. The most important study that includes the influence of the electric conductivity on MBN was conducted by Alessandro Bertotti [1,9] in electrical steels, with a model called ABBM. In this model, it is considered that the amplitude of an elementary MBN jump is directly proportional to the difference between the applied magnetic field and the local coercive field of the defects, and it is inversely proportional to the electric conductivity. Nevertheless, in this study, no specific analysis is performed concerning the influence of the electric conductivity on MBN parameters.

On the other hand, it has been shown that the r.m.s of the MBN signal (Vrms) increases proportionally with carbon content, from 0.02 wt% C to 0.45 wt% C [7]. This fact has been attributed to an increase in the number of defects interacting with domain walls. However, the MBN is also influenced by several electric and magnetic properties of the material, whose influence has not been well understood yet. Electric conductivity could be relevant in the study of the influence of carbon content on MBN because a change in carbon content also affects the material´s electric conductivity. Recently, a study conducted in carbon steels shows that the electric conductivity has a strong dependence on carbon content within the range of 0.06–1.22 wt% C [10]. This result also reveals that it is necessary to study the influence of the electric conductivity on

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MBN in order to separate its effect from the influence of the material's microstructure.

## 2. The model

### *2.1. Description of the coupled model of magnetic flux density and MBN.*

In a previous work by Perez-Benitez et al. [11] proposes a model for the simulation of the MBN. The equations used in this model for the computing of the magnetic flux density are the two-dimensional quasi-static magnetic equations without considering the influence of induced currents. The coupling of these electromagnetic equations and the MBN phenomenon is performed using the phenomenological model proposed by Pérez-Benitez et al. [7]. The MBN is modeled considering that the MBN jumps are produced by the interaction between domain walls with pinning sites (where the local coercive field distribution is given by a Gaussian distribution function). Furthermore, the interactions between domain walls and pinning sites are taken into account considering that the MBN occurs into a grid of 180° domains couples. Fig. 1 shows the arrangement for simulation of MBN used in this work [11].

The model proposed in the present work is based in the model presented in [11]. However, unlike this model, in the proposed model eddy currents are taken into account.

Thus, the quasi-static magnetic equation for the present model is

$$\sigma\frac{\partial\vec{A}}{\partial t}+\nabla\times\left(\mu^{-1}\nabla\times\vec{A}-\vec{M}^{*}\right)=\vec{J}^{e} \tag{1}$$

with

$$\vec{B}=\nabla\times\vec{A} \tag{2}$$

and

$$\vec{M}^{*}=\frac{\vec{M}_R}{\mu_r} \tag{3}$$

where $\vec{B}$ is the magnetic flux density, $\vec{A}$ is the magnetic vector potential, $\mu$ is the magnetic permeability, $\mu_r$ is the relative magnetic permeability, $\vec{M}_R$ is the remnant magnetization, $\sigma$ is the electric conductivity and $\vec{J}^{e}$ is the current density.

In the finite difference method approach, the region of analysis

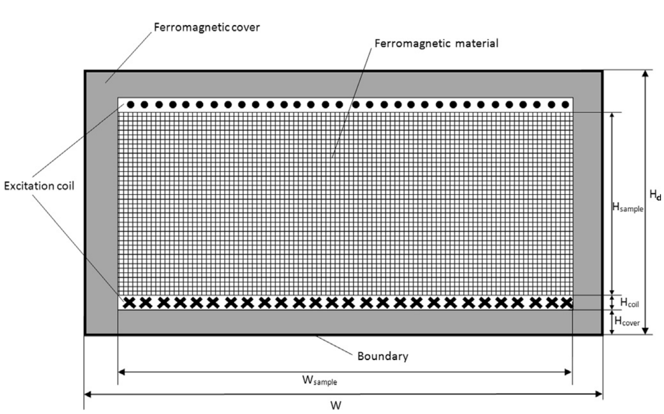


**Fig. 1.** Arrangement used for the finite difference simulation of MBN. the main part of this arrangement Is the ferromagnetic sample located in the middle, where the MBN occurs. this sample Is wound by an excitation coil that generates the applied magnetic field, and they are surrounded by a ferromagnetic cover to concentrate the magnetic flux density.

is formed by a grid with $(N+1)$ by $(M+1)$ divisions. Each node of the grid has $(i,j)$ coordinates, where $i$ indicates the row and $j$ indicates the column of the node.

Using the finite difference approach, Eq. (1) can be expressed as

$$\begin{pmatrix} T_1 & -I_1 & & \\ -I_1 & \ddots & \ddots & \\ & \ddots & & -I_{(M-1)} \\ & & -I_{(M-1)} & T_M \end{pmatrix}\begin{pmatrix}\mathbf{A}_1\\ \mathbf{A}_2\\ \vdots\\ \mathbf{A}_M\end{pmatrix}=\begin{pmatrix} b_1-h^2(\mathbf{j}_1-J_1)+h\mathbf{m}_1\\ b_2-h^2(\mathbf{j}_2-J_2)+h\mathbf{m}_2\\ \vdots\\ b_M-h^2(\mathbf{j}_M-J_M)+h\mathbf{m}_M\end{pmatrix} \tag{4}$$

where the sub-matrixes $T_i$, and $I_i$ as well as the boundary conditions $b_i$ are the same that in [16]. On the other hand, the induced currents $J_i$ are given by

$$\begin{aligned} J_i&=\left(\sigma_{1i}\frac{\partial A_{1i}}{\partial t},\ \ldots,\ \sigma_{Ni}\frac{\partial A_{Ni}}{\partial t}\right)^T\\ &=\left(\sigma_{1i}\frac{A^{t}{}_{1i}-A^{t-1}{}_{1i}}{\Delta t},\ \ldots,\ \sigma_{Ni}\frac{A^{t}{}_{Ni}-A^{t-1}{}_{Ni}}{\Delta t}\right)^T i=1,\ \ldots,\ M \end{aligned} \tag{5}$$

and magnetization term is given by

$$\begin{aligned} m_i=\Bigg[&\left(\frac{m^{y}_{21}}{\mu_{r21}}-\frac{m^{y}_{01}}{\mu_{r01}}\right)\\ &-\left(\frac{m^{x}_{1(i+1)}}{\mu_{r1(i+1)}}-\frac{m^{x}_{1(i-1)}}{\mu_{r1(i-1)}}\right),\ \ldots,\ \left(\frac{m^{y}_{(N+1)1}}{\mu_{r(N+1)1}}-\frac{m^{y}_{(N-1)1}}{\mu_{r(N-1)1}}\right)\\ &-\left(\frac{m^{x}_{N(i+1)}}{\mu_{rN(i+1)}}-\frac{m^{x}_{N(i-1)}}{\mu_{rN(i-1)}}\right)\Bigg]^T \end{aligned} \tag{6}$$

$i=1,\ \cdots,\ M$

where $m^{x}_{i,j}$ and $m^{y}_{i,j}$ are the components of the remnant magnetization $m_{i,j}$ at the grid nodes $(i,j)$, in the $x$ and $y$ directions, respectively.

An alternative method to solve Eq. (1) can be obtained by using an iterative method, by means of

$$\begin{aligned} A^{t}_{ij}=\frac{1}{C_{ij}}\Bigg(&\frac{1}{\mu_{\left(i-\frac{1}{2}\right)j}}\tilde{A}^{t}_{(i-1)j}+\frac{1}{\mu_{\left(i+\frac{1}{2}\right)j}}\tilde{A}^{t}_{(i+1)j}+\frac{1}{\mu_{i\left(j-\frac{1}{2}\right)}}\tilde{A}^{t}_{i(j-1)}+\frac{1}{\mu_{i\left(j+\frac{1}{2}\right)}}\tilde{A}^{t}_{i(j+1)}\\ &-h\mu_0\left[\left(\frac{m^{y}_{21}}{\mu_{21}}-\frac{m^{y}_{01}}{\mu_{01}}\right)-\left(\frac{m^{x}_{1(i+1)}}{\mu_{1(i+1)}}-\frac{m^{x}_{1(i-1)}}{\mu_{1(i-1)}}\right)\right]-h^2\mu_0 J_{ij}+\sigma_{ij}\mu_0\frac{h^2\left(\tilde{A}^{t}_{ij}-A^{t-1}_{ij}\right)}{\Delta t}\Bigg) \end{aligned} \tag{7}$$

where $C_{ij}$ is the same as in [16]. In the case of Eq. (7), an iterative process is required in order to obtain the value of $A^{t}_{ij}$. Eq. (7) is evaluated repeatedly for all nodes $(i,j)$, considering that $A^{t}_{ij}$ is the value of the magnetic vector potential in node $(i,j)$ at a given time $t$ for the current iteration, and $\tilde{A}^{t}_{ij}$ is the vector potential in node $(i,j)$ for the previous iteration $(t-1)$. The iterative process stops when condition $\sum_{j}^{M}\sum_{i}^{N}\left(\frac{A^{t}_{ij}-\tilde{A}^{t}_{ij}}{A^{t}_{ij}}\right)^2\le\xi$ is accomplished, where $\xi$ is a convergence value, fulfilling the condition of $10^{-11}\le\xi\le 10^{-12}$.

The remnant magnetization components $m^{x}_{i,j}$ and $m^{y}_{i,j}$ change according to

$$m^{x}_{i,j}=\begin{Bmatrix}-M_s & H^{x}_{ij}\le hc_{i,j}\\ M_s & H^{x}_{ij}>hc_{i,j}\end{Bmatrix} \tag{8}$$

and

$$m^{y}_{i,j}=\begin{Bmatrix}-M_s & H^{y}_{ij}\le hc_{i,j}\\ M_s & H^{y}_{ij}>hc_{i,j}\end{Bmatrix} \tag{9}$$

where $h_{cij}$ and $H_{ij}$ are the local coercive fields acting on domain