MODEL OF MAGNETIC REVERSAL IN FERROMAGNETIC LAMINATION

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ABSTRACT

Conducting lamination with a one central ferromagnetic layer and two outer non-ferromagnetic layers is investigated. The concept of a single rigid 180° domain wall spreading through the axially magnetized ferromagnetic layer is used to calculate induced eddy currents in lamination. Non-homogeneous magnetic field intensity generated by eddy currents is analysed.

Keywords: *domain wall, eddy currents, eddy currents field, ferromagnetic lamination, magnetic reversal, Maxwell equations*

1. INTRODUCTION

The eddy currents distribution for a single plane domain wall moving in a rectangular ferromagnetic bar was studied by Williams et al. [1]. Based on this work the extended model was developed containing a rectangular ferromagnetic core and two conducting non-ferromagnetic layers - shell (see Fig. 1) [2]. It was shown that conductivity and thickness of non-ferromagnetic layers (NFL) with respect to the thickness of a ferromagnetic layer (FML) play a very important role in calculations of domain wall velocity and power losses. The movement of a single domain wall was also studied by Colaiori et al. [3] by means of diffusion equation for eddy currents field, i.e. there is a finite time delay between the wall displacement and the establishment of the eddy currents. In this article the quasi-static approximation is introduced, where permeability μ is negligible within domains, and reduced Maxwell equations are used in Sec. 3. The influence of domain wall non-zero thickness on eddy currents losses produced during wall movement through the sample is very small in case of strong axial magnetic anisotropy [4]. From this reason the approximation of the zero domain wall thickness is fully valid for the model described in Sec. 2.

2. MODEL DESCRIPTION

Let us consider a rectangular sample with dimensions $x \in [\ -L_1\ ,\ L_2\ ]$, $y \in [\ -h/2\ ,\ h/2\ ]$, and infinite in the *z* direction. The sample contains three conducting layers, two outer layers are not ferromagnetic and the central one is ferromagnetic with uniform antiparallel magnetization with respect to *z* direction. If an external magnetic field of intensity *H* is applied in *z* direction, magnetic reversal of FML occurs by the propagation of a single rigid 180° domain wall from the left to the right sample boundary as displayed in Fig. 1. The origin of the coordinate system is placed in a centre of a moving domain wall (x=0). It should be pointed out that L_1 and L_2 are variable distances of the domain wall from left and right sample boundary, respectively. Thus the sample width is L_1+L_2. The FML thickness is denoted *d*.

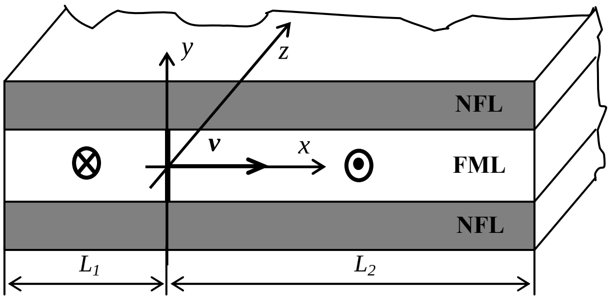

Fig. 1 Domain wall movement in ferromagnetic layer (FML)

3. EDDY CURRENTS CALCULATIONS

Generally the theory of eddy currents is based on a diffusion equation solution [5]. The following calculations are done on the assumption that electric and magnetic fields are propagated instantaneously (displacement current is neglected). The current density $\boldsymbol{j}$ is the solution of the differential equations

$$\nabla^2\boldsymbol{j}=0,\quad \mathrm{rot}\,\boldsymbol{j}=0,\quad \mathrm{div}\,\boldsymbol{j}=0 \tag{1}$$

Using the boundary condition: $\boldsymbol{j}_n$=0, normal component of $\boldsymbol{j}$ is equal to zero on all outer sample surfaces, gives

$$\begin{aligned} j_x(x,y) &= -\sum_{n=1}^{\infty} D_n \sinh\left[\frac{n\pi}{h}\left(L_{1,2}-x\right)\right]\cos\left[\frac{n\pi}{h}\left(y-\frac{h}{2}\right)\right], \\ j_y(x,y) &= -\sum_{n=1}^{\infty} D_n \cosh\left[\frac{n\pi}{h}\left(L_{1,2}-x\right)\right]\sin\left[\frac{n\pi}{h}\left(y-\frac{h}{2}\right)\right], \end{aligned} \tag{2}$$

where L_1 is for interval $x\leq 0$ and L_2 is for interval $x\geq 0$. Additional boundary condition should be applied within the sample at the domain wall position (x=0)

$$\mathrm{rot}\boldsymbol{j}=-\gamma\mu_0\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t}, \tag{3}$$

where d$\boldsymbol{M}$/dt is a rate of magnetization change, γ is the sample conductivity and μ_0 is magnetic permeability.

Application of condition (3) in (2) results in specification of coefficients D_n:

$$D_n = \mp \frac{4\gamma\,\mu_0\, M_S\, v\, \sin\left(\frac{n\pi}{2}\right)\sin\left(\frac{n\pi d}{2h}\right)}{n\pi\cos\left(\frac{n\pi L_{1,2}}{h}\right)}, \tag{4}$$

for $n = 1, 2, 3, \ldots$, where v is domain wall velocity and the + sign is valid for $j_y(x,y)$ with L_1 in interval $x \leq 0$ only.

4. EDDY CURRENTS FIELD

Non-homogeneous magnetic field generated by eddy currents can be calculated from (2). Using Biot-Savart law [6] gives us the eddy currents field intensity at the wall position (x=0)

$$H_z(0,y) = \frac{1}{4\pi}\iint \frac{j_x(y-y') - j_y x'}{\left[x'^2 + (y-y')^2\right]^{3/2}}\, dx'dy', \tag{5}$$

where the integration is in the cross section of the rectangular sample $x' \in [\,-L_1\,,\,L_2\,]$, $y' \in [\,-h/2\,,\,h/2\,]$. Figure 2 displays reduced eddy currents field distribution at the domain wall calculated from (5). The eddy currents field $H_z(0,y)$ is antiparallel to external driving field and it dampens domain wall acceleration. This process is known as eddy currents damping. The application of general form of Biot-Savart law [6] allows us to determine eddy currents field $H_z(x,y)$ all over the sample. As the local maximum of $H_z(x,y)$ can be find at the centre of the sample (y=0), the distribution of maximum $H_z(x,0)$ in the x axis was calculated (see Fig. 3, 4).

5. RESULTS AND DISCUSSION

Calculated distribution of the eddy current field intensity at the wall (x=0) shows the maximum intensity at the centre of the domain wall and the smooth decrease towards the boundary-lines between ferromagnetic and non-ferromagnetic layers (see Fig. 2).

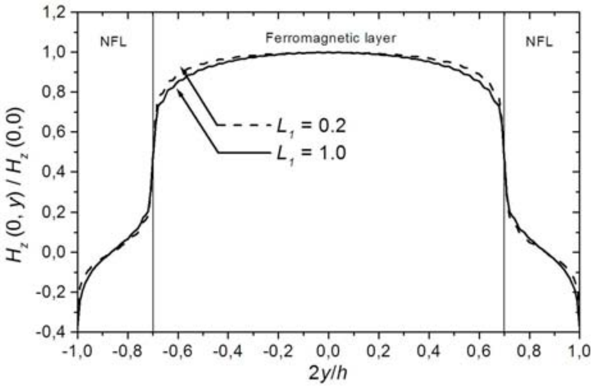

Fig. 2 Distribution of the reduced eddy current field intensity at the rigid plane domain wall in the middle of sample L_1 = 1 and near the left sample boundary L_1 = 0.2 (dashed curve). Boundary-lines between ferromagnetic and non-ferromagnetic layers (NFL) are displayed. The sample width is $L_1 + L_2$ = 2.

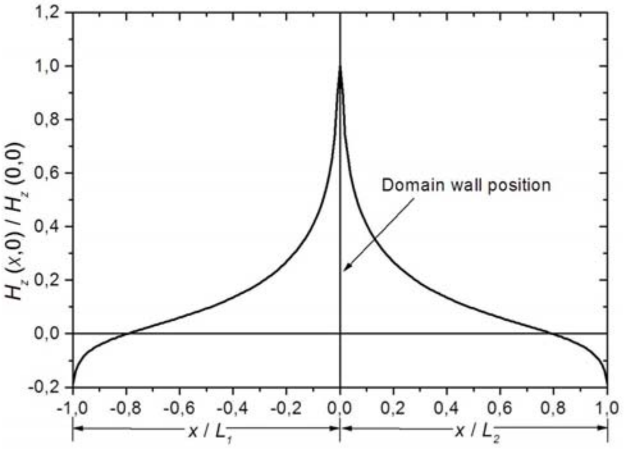

Fig. 3 Distribution of the reduced eddy current field intensity through the sample in the x axis (y = 0). The position of the wall (x = 0) is symmetric with respect to the left and right sample boundary.

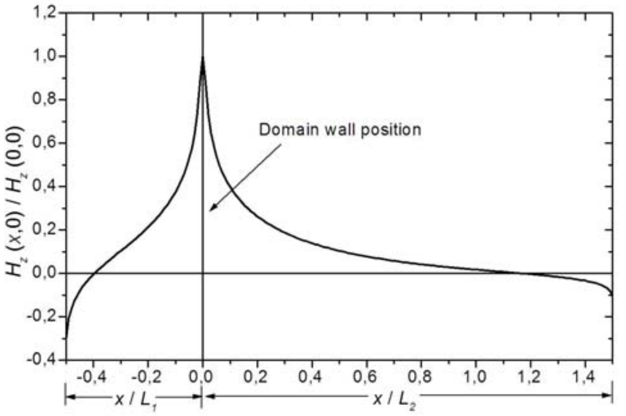

Fig. 4 Distribution of the reduced eddy current field intensity running through the sample in the x axis (y = 0). The position of the wall (x = 0) is asymmetric with respect to the left and right sample boundary.

The shape of distribution is practically the same whether the wall is in the middle of the sample or near by the sample boundary. The distribution maximum is always situated in the x axis (y=0). The average value of eddy current field intensity $H_z(0,y)$ inside the ferromagnetic layer at the domain wall position is non-zero. As the orientation of $H_z(0,y)$ is antiparallel to external driving field H the movement of the wall is damped till an equibalance of $H_z(0,y)$ and H occurs (eddy currents damping). In case of flexible domain wall we can also consider a wall bending but in the presented model of the rigid wall this is neglected. In non-ferromagnetic layers the average value of $H_z(0,y)$ is equal to zero. Figures 3, 4 display how the distribution of the maximum $H_z(x,0)$ is running through the sample along the x axis. We observe a rapid decrease of $H_z(x,0)$ with x to zero value. But there is a transition interval near the left and right sample boundary where H_z changes its antiparallel orientation to the parallel one with respect to external field H. If the position of the wall is symmetric with respect to the left and right sample boundaries the transition intervals are identical (see Fig. 3). But in case of asymmetric position of the wall (see Fig. 4) the eddy currents intensity $H_z(x,0)$ is considerably higher in transition interval which is closer to the moving domain wall.

6. CONCLUSION

The proposed theoretical model deals with magnetic reversal of the rectangular sample consisting of one central ferromagnetic layer and two outer conductive non-ferromagnetic layers. The magnetic reversal in external magnetic field is connected with propagation of one single domain wall through the ferromagnetic layer. Induced eddy currents spread through the whole volume of the sample. That means that the presence of two conductive non-ferromagnetic layers significantly affects the generated eddy currents field in the sample. Just the proposed geometry of the sample allows us to calculate exactly the eddy currents distribution and to determine the generated eddy currents field in the sample as well. In the distribution of eddy currents intensity $H_z(x,0)$ along x axis the existence of transition intervals near the left and right sample boundaries was shown. In case of asymmetric position of the domain wall with respect to the left and right sample boundary the $H_z(x,0)$ is considerably higher in this transition interval which is closer to the moving wall. This can give an opportunity to nucleate a new domain wall in a real ferromagnetic sample preferably at the boundary with higher $H_z(x,0)$.

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BIOGRAPHIES

Jozef Kravčák was born on 17.03.1972. In 1995 he graduated (MSc) at the department of Physics of Condensed matter of the Faculty of Science at P. J. Šafárik University in Košice. He defended his PhD in the field of magnetism and magnetic materials in 2004; his thesis title was “Directional ordering in ferromagnetic alloys“. Since 1997 he is working as an assistant professor with the Department of Physics of the Faculty of Electrical Engineering and Informatics at Technical University in Košice. His scientific research is focusing on dynamic magnetic processes in magnetic materials.