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# Micromagnetic Analysis of Fast Precessional Switching

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**Abstract**

The precessional switching process in magnetic recording thin-films is investigated by means of micromagnetic simulations. The uniform mode theory is used to predict the right time instant to switch off the field and the time tolerance which still allows successful switching. This analysis is performed for different values of applied field and anisotropy constant. We verified that the uniform mode theory provides accurate information about the tolerance on the switching time for moderately soft materials.



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The fast switching of magnetic thin-film media is one of the main issues in the area of magnetic data storage technologies. The conventional way to realize magnetization reversal in thin films consists of applying a sufficiently large magnetic field almost antiparallel to the initial magnetization state. If the field is strong enough and applied for sufficient time, the initial configuration becomes unstable and the magnetization is forced to switch to the reversed state which, instead, is a minimum of the free energy of the system. Thus, the resulting reversal dynamics is driven by dissipative processes. This conventional switching is often referred to as "damping switching". Recently, the precessional motion of magnetization has been used to realize the switching of thin films and particles [1,2]. In this kind of switching, the external field is applied in the film plane and is approximately orthogonal to the initial magnetization state. This field produces a torque, that pushes the magnetization out-of-plane, which creates a strong demagnetizing field, leading the magnetization to precess around it. The resulting magnetization dynamics is faster and less energy-consuming. Since this magnetization dynamics consists essentially of a precessional motion around the strong demagnetizing field, one has to switch the field off precisely when precession has brought the magnetization state close to its reversed orientation. Therefore, the applied field pulse duration is a crucial issue, while in damping switching this does not happen. In this framework, it is important to investigate which tolerance on the choice of the pulse duration allows a successful switching. In this paper, we consider the switching process of a magnetic rectangular thin-film: the thickness is $c = 5$ nm, the large and short edge length are $a = 500$ nm and $b = 250$ nm, respectively. The thin-film medium has a uniaxial magneto-crystalline anisotropy. The easy axis is along the $x$-axis (long axis), the exchange stiffness constant is $A = 1.3 \times 10^{-11}$ J/m, the saturation polarization is $J_s = 1$ T ($M_s \approx 795$ kA/m) and the damping constant is $\alpha = 0.02$; the exchange length of the material is $l_{\mathrm{exc}} = \sqrt{(2A)/(\mu_0 M_s^2)} = 5.7$ nm. We assume that the magnetization dynamics of the thin-film is described by the Landau-Lifshitz-Gilbert equation, namely:

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \quad , \qquad (1)$$

where $\gamma$ is the absolute value of the gyromagnetic ratio, $\alpha$ is the damping constant and $\mathbf{H}_{\mathrm{eff}}$ is the effective field

$$\mathbf{H}_{\mathrm{eff}}\,(\mathbf{M}(.)) = \mathbf{H}_m + \mathbf{H}_{\mathrm{exc}} + \mathbf{H}_{\mathrm{an}} + \mathbf{H}_a \quad . \qquad (2)$$

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In Eq. (2) $\mathbf{H}_a$ is the applied field, $\mathbf{H}_{\mathrm{exc}}$ is the exchange field, $\mathbf{H}_{\mathrm{an}}$ the anisotropy field and $\mathbf{H}_m$ the magnetostatic (demagnetizing) field. In micromagnetic simulations Eq. (1) is integrated numerically using a backward differentiation formula [3]. The spatial discretization is done using the finite element method on a mesh consisting of tetrahedrons with mesh edge length of 5 nm $< l_{\mathrm{exc}}$. A hybrid finite element boundary element method [4] is used to solve the magnetostatic problem.

It has been shown in Ref. [5] that the precessional switching process, for similar geometry and material parameters, can be reasonably considered a quasi-uniform process, so that the uniform mode theory can be applied.

For this reason, we approximate the thin-film with a flat ellipsoid characterized by the demagnetizing factors $N_x$, $N_y$, $N_z$ such that $N_x, N_y \ll N_z \approx 1$. Since we deal with media having small dissipative effect, we can study the conservative magnetization dynamic by means of the undamped Landau-Lifshitz equation:

$$\frac{d\mathbf{m}}{dt} = -\mathbf{m} \times \mathbf{h}_{\mathrm{eff}} \quad , \tag{3}$$

where time is measured in units of $(\gamma M_s)^{-1}$ and the (normalized) effective field $\mathbf{h}_{\mathrm{eff}} = \mathbf{H}_{\mathrm{eff}}/M_s$ has now the following form, provided that the exchange field is zero:

$$\mathbf{h}_{\mathrm{eff}} = -D_x m_x \mathbf{e}_x - D_y m_y \mathbf{e}_y - D_z m_z \mathbf{e}_z + h_a \mathbf{e}_y \quad . \tag{4}$$

The coefficients $D_x < D_y < D_z$ take into account the demagnetizing effects and magnetocrystalline anisotropy, $h_a$ is the normalized applied field and $\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z$ are the unit vectors along the Cartesian axes $x, y, z$, respectively. The relationship between the material parameters and the coefficients $D_x$, $D_y$, $D_z$ are:

$$D_x = N_x - \frac{2K_1}{\mu_0 M_s^2},\ D_y = N_y,\ D_z = N_z. \tag{5}$$

We follow now the approach proposed in Ref. [6] to derive the expression of the external field pulse duration $T_s$ and the time window $[t_1, t_2]$ around it that leads to a successful switching. To this end we exploit the motion integrals of Eq. (3):

$$m_x^2 + m_y^2 + m_z^2 = 1 \tag{6}$$

$$\frac{1}{2}D_x m_x^2 + \frac{1}{2}D_y m_y^2 + \frac{1}{2}D_z m_z^2 - h_a m_y = g_0 \ , \tag{7}$$

representing magnetization magnitude conservation and energy conservation, respectively, with $g_0$ being the initial energy. It has been shown in Ref. [6] that, by considering the appropriate linear combination of Eqs. (6) and (7), the precessional magnetization motion occurs along the elliptic curve:

$$m_x^2 + k^2(m_y - a_y)^2 = p^2 \quad , \tag{8}$$

confined in the unit disk $m_x^2 + m_y^2 \leq 1$. In Eq. (8) $k^2 = (D_z - D_y)/(D_z - D_x)$, $a_y = -h_a/(D_z - D_y)$, $p^2 = k^2 a_y^2 + (D_z - 2g_0)/(D_z - D_x)$. It is possible to express the elliptic curve (8) in parametric form:

$$m_x = -p\cos u \quad , \quad m_y = a_y + \frac{p}{k}\sin u \quad , \tag{9}$$

where $u \in [0, 2\pi]$ is the parameter. By substituting Eqs. (9) in Eq. (3) and separating variables one ends up with the following differential equation

$$\frac{du}{f(u)} = k(D_z - D_x)dt\, , \tag{10}$$

where $f(u) = \sqrt{1 - p^2\cos^2 u - (a_y - (p/k)\sin u)^2}$, which gives the relation between the parametric variable $u$ and time. By using Eq. (10) it is possible to derive the following expressions for the switching time $T_s$ and the time window $[t_1, t_2]$ for switching the applied field off such that $t_1 < T_s < t_2$:

$$t_1 = \int_{u_0}^{u_1} \frac{du}{k(D_z - D_x)f(u)} \quad , \tag{11}$$

$$t_2 = t_1 + 2\int_{u_1}^{u_2} \frac{du}{k(D_z - D_x)f(u)} \quad , \tag{12}$$

$$T_s = (t_2 + t_1)/2 \quad . \tag{13}$$

In the last equations the value of the parameters $u_0$, $u_2$ can be found by using parametric Eqs. (9) to find the intersections between Eq. (8) and the unit circle $m_x^2 + m_y^2 = 1$. The value $u_1$ can be found from the intersection between Eq. (8) and the ellipse $m_x^2 + k^2 m_y^2 = k^2$ delimiting the high energy region, by using parametric Eqs. (9). The details of this analysis can be found in Ref. [6]. It is important to notice that, in the conservative case, $t_1$ is the time instant at which the magnetization enters the potential well around the reversed state, $t_2$ is the time instant at which magnetization goes out from that potential well and $T_s$ is the time instant at which the magnetization is exactly in the reversed state. Thus, in a slightly dissipative case, switching the

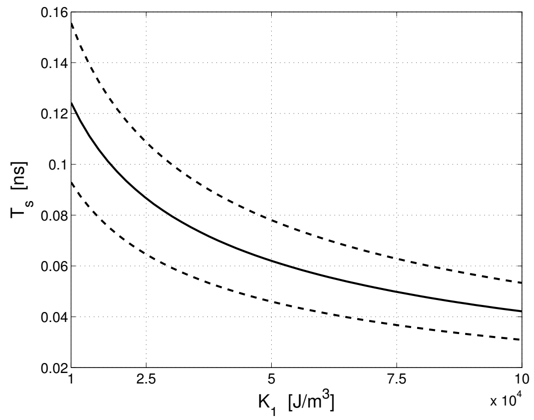


Fig. 1. Plot of switching time $T_s$ (solid line), $t_1$,$t_2$ (dashed line). $h_a = D_y - D_x$, $D_x$ according to Eq. (5), $D_y = 0.0175$, $D_z = 0.9763$.

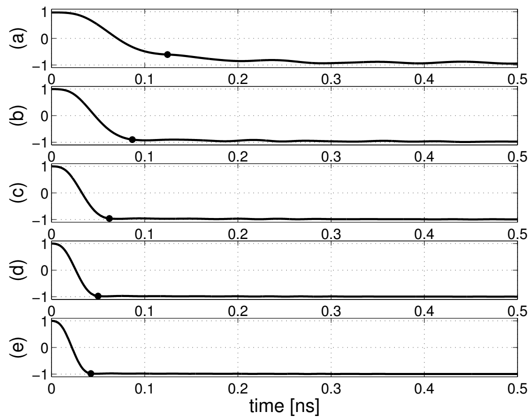


Fig. 2. Plot of $m_x$ vs time; (a) $K_1 = 10^4$; (b) $K_1 = 2.5\times10^4$; (c) $K_1 = 5\times10^4$; (d) $K_1 = 7.5\times10^4$; (e) $K_1 = 10\times10^4$. In each plot the switching time $T_s$ is emphasized with a black dot.

applied field off when $t_1 < t < t_2$ lets the magnetization relax towards the reversed state due to the damping effect. In Fig. 1 the plot of the time instants $t_1$, $T_s$, $t_2$ is reported as a function of the anisotropy constant $K_1$. The applied field $h_a = D_y - D_x$ is related to $K_1$ through Eq. (5). It is important to underline that the time window for switching the field off is reasonably wide because, in the analyzed interval of $K_1$, is $t_1 < 0.75 \times T_s$ and $t_2 > 1.25 \times T_s$, that is, a tolerance of at least 25% on the switching time is allowed. On the basis of the above analysis we performed a set of micromagnetic simulations of precessional switching experiments. Initially, the thin-film is saturated along the positive $x$-axis, then it is relaxed to the remanent state. At time $t = 0$ the rectangular external field pulse is applied $H_a = (D_y - D_x)M_s$ until time $t = T_s$ at which the field is switched off and the magnetization relaxes towards equilibrium. We performed different simulations for different values of $K_1$, reported in table below:

| $K_1$ [$10^4$ J/m$^3$] | 1.0 | 2.5 | 5.0 | 7.5 | 10 |
|---|---|---|---|---|---|
| $H_a$ [kA/m] | 30.88 | 60.88 | 110.88 | 160.88 | 210.88 |
| $T_s$ [ps] | 124.3 | 86.6 | 62.0 | 49.8 | 42.1 |
| $t_1$ [ps] | 92.9 | 64.6 | 46.0 | 36.7 | 30.9 |
| $t_2$ [ps] | 155.6 | 108.7 | 78.0 | 62.9 | 53.3 |

The results are reported in Fig. 2 where the switching time $T_s$ is emphasized. One can clearly see that for moderately low values of $K_1$ (Fig. 2a) at $t = T_s$ magnetization is not exactly close to the reversed state, but micromagnetic simulations show that the higher is the applied field strength, the better is the agreement with the uniform mode theory. By moderately increasing the value of the anisotropy constant there is a very good agreement with the above prediction and the remaining oscillation after $t = T_s$ tends to be very close to the magnetization reversed state (Fig. 2(b)-(e)). Next, we chose to verify the prediction of the uniform mode theory regarding the time window for switching the field off. We analyze, for sake of brevity, the case of anisotropy constant $K_1 = 2.5\times10^4$ J/m$^3$. The applied field is $H_a = (D_y - D_x)M_s = 60.88$ kA/m. The results are reported in Fig. 3, showing the high accuracy of the uniform mode theory prediction. In fact, switching the applied field off just few picoseconds after time $t = t_2$ (Fig. 3b) or just a few picoseconds before time $t = t_1$ (Fig. 3d) leads to non-successful switching, while switching the applied field off just few picoseconds before time $t = t_2$ (Fig. 3a) or just a few picoseconds after time $t = t_1$ (Fig. 3c) leads to successful switching. The prediction applies with better accuracy with higher anisotropy constant values. Thus, we can conclude that, in precessional switching experiments on thin-film media constituted of moderately soft materials, the time window for switching the applied field off can be derived by using the uniform mode theory with a very high accuracy.

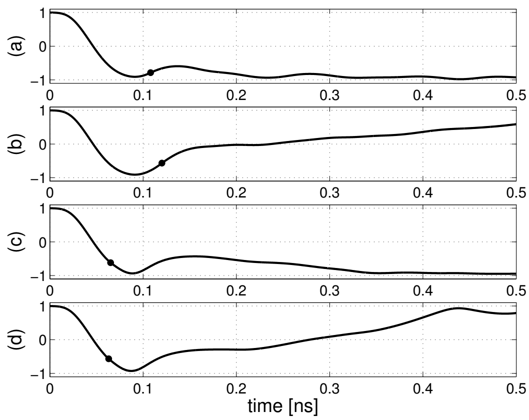


Fig. 3. Plot of $m_x$ vs time. The field is switched off at time (a) $t = 108$ ps; (b) $t = 120$ ps; (c) $t = 65$ ps; (d) $t = 63$ ps.

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